THE ROLE OF PLANKTON IN THE ENERGY TRANSFER TO THE SEDIMENT IN DUBH LOCHAN

Thesis submitted in accordance with the requirements of the University of Glasgow for the degree of Doctor of Philosophy

by

Abul Kalam Mohammed Sirajul Islam

Department of Zoology

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DEDICATION

To my late mother who did so much for my education but unfortunately could not see this Thesis because of her sudden death during the course of the study.

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SUMMARY

The fate of photosynthetically fixed energy and the role of plankton in the energy flow to the sediment through detrital pathway is reported. Some selected physico-chemical conditions of the habitat, phytoplankton and zooplankton biomass, seasonal patterns of individual species and primary production of phytoplankton were studied from October, 1983 to September, 1985. Seston biomass, composition, chemistry and energetics were studied from March, 1985 to February, 1986. Chemistry and the energetics of the sediment were studied from July, 1985 to June, 1986. Benthos biomass and energetics were studied from March, 1985 to February, 1986.

Chemical conditions especially pH, conductivity, nitrate, orthophosphate and silicate showed great variations since Klarer's (1978) study, conducted 10 years earlier.

Phytoplankton biomass showed a single summer peak during June and July.

Zooplankton biomass showed three distinct seasonal peaks during mid to late spring, late summer to early autumn and in late autumn to early winter.

Seston biomass showed three distinct seasonal peaks during mid spring, late summer and mid autumn although high levels were also observed in winter.

Nitrogen and phosphorus concentrations in the sediment were also higher at station 1 than at station 2. Both organic carbon and the energy content of the sediment were much higher during the summer months than the rest of the period.

Benthos biomass showed two distinct seasonal peaks at station 1, during spring and autumn and a single summer peak at station 2.

On an annual basis, 0.87% of the energy was transformed from phytoplankton to zooplankton ranging from 0.08% in October to 5.89% in February.

Seventy seven percent of the energy was channelled through seston. Seston production greatly exceeded primary production from November to February, 1986.

The energy transfer from primary production during late spring to mid summer was not reflected in the sediment, instead the highest level was observed in August and September when primary production was very low.

Benthos production was independant of primary production in deep water at station 1 but in shallow water at station 2, it closely followed primary production.

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CHAPTER — 1.

GENERAL INTRODUCTION

Studies on the bioenergetics or energy flow are becoming increasingly important in aquatic ecosystems, dating from the trophic dynamic model of ecosystem structure (Lindemann, 1942). During the last decade the body of data concerning energy flow in lake ecosystems has increased markedly (Jonasson, 1972 & 1981; Kajak et al., 1972; Morgan & McLusky, 1974). The number of organisms live in an ecosystem depends on the rate at which energy flows through the biological part of the system and are exchanged with the adjacent systems.

Non energy yielding materials circulate, but energy does not. Nitrogen, carbon, water and the other materials of which living organisms are composed may recirculate many times between living and non-living entities but energy is used once by a given organism or population, is converted into heat and is soon lost from the ecosystem. Life is kept going by the continuous flow of energy in the form of sun light (Odum, 1963; Fisher & Likens, 1973). Therefore, the interaction of energy and the materials in the ecosystem is extremely important. By far the most important input of chemical energy into lentic ecosystem is by the

photosynthesis of phytoplankton which are considered as primary producers. Thus the chemical energy flows through the ecosystem in various ways to the secondary or tertiary producers through repeated eating and being eaten in complex natural communities and could be referred as grazing food chain. At each transfer of energy from one organism to another, or from one trophic level to another, a large part is degraded into heat. The shorter the food chain, or the nearer the organism to the beginning of the food chain, the greater the available chemical energy to the organism. So phytoplankton as primary producers and zooplankton as secondary producers together play a very important role in the energy transfer at different trophic levels in the aquatic ecosystems.

After the death and decomposition of plankton, they join detritus. It has been apparent for a long time that organic detritus play a very important role in the structure and function of aquatic ecosystems. Organic matter functions as an energy reservoir, which may be more rapidly or more slowly utilized depending on the functional requirements of the system (Saunders, 1980) and could be regarded as decomposer food chain. Other autochthonous organic matter (originating mainly from aquatic macrophytes) and allochthonous organic matter (originating from outside sources) could also be important sources of energy input in

lake ecosystems. However, they were not separated in the detrital dynamics during the present study.

The efficiency of energy transformation from one trophic level to another depends upon the nature of degradation and also the nature of the subsequent transformation in complex ecosystems. It also depends upon environmental conditions such as light availability, temperature, dissolved gases, essential nutrients etc., (Jonasson, 1979). Kozlovsky (1968) reviewed the literature on ecological efficiencies and defined these as non-dimensional ratios of various parameters of energy flow in or between the trophic levels of a natural community, in or between populations of organisms or in or between organisms. Each ecosystem has its own way of energy transformation and dispersion system. Ecological bioenergetic studies are, therefore, very important in understanding fundamental growth processes in an aquatic ecosystem.

A proper understanding of the energy flow at different trophic levels and also in different seasons in a particular habitat is essential from fisheries point of view. Many fish are plankton feeders, some are phytoplankton feeders and some feed on both phytoplankton and zooplankton. Some fish feed on organic debris and detritus and others feed on littoral or benthic animals. Again some fish are pelagic

feeders, some are bottom feeders and others feed in between or in different trophic levels either in different seasons or even in different times in a day depending upon the availability of food. Therefore the proper growth of fish and the successful management of a fishery depends directly or indirectly upon the role of the plankton in the energy transfer at different trophic levels in a particular habitat.

Mann (1969) reviewed the evolution of methodology concerning bioenergetic studies in aquatic ecosystems. The International Biological Programme (IBP) reviewed and described the standard techniques in measuring both primary productivity (Vollenweider, 1969) and secondary productivity (Edmondson and Winberg, 1971) in aquatic ecosystems.

One of the first attempts to construct an annual energy budget of a lake was that of Juday (1940). The trophic dynamic aspect of lake ecosystem was reported by Lindemann (1942) and Hutchinson (1957) summarized the works concerning energy budgets of lakes during the first 20 years of study. Slobodkin (1960) discussed the theory of energy budgets and also recommended some models to study the energy budgets in the lake ecosystems. Mann (1969) reviewed the important studies related to the trophic dynamics of aquatic ecosystems. Different approach to ecological energetics and

the whole concept were reviewed by Phillipson (1975). Different parameters of energy budget and the interrelationship between trophic levels were reviewed by Duncan & Klekowski (1975). There have been recent reviews of studies on ecological energetics on a world wide basis under the auspices of the IBP. (Le Cren & Lowe - McConnell, 1980).

Energy flow studies on temperate lakes have mainly been confined to phytoplankton production and to some extent on zooplankton production but studies have been carried out in Arctic Canada and Soviet Union on whole ecosystems (Jonasson, 1981). However, the studies in the past were mainly concerned with the grazing pathway and decomposing pathway has long been neglected (Melchiorri-Santolini & Hopton, 1972). Very little is known about non-living organic matter and the process of its transformation and decomposition in aquatic ecosystems (Saunders, 1980). Energetic studies were mainly confined to individual compartments like seston and sediment. Few works on seston include Hallegraeff (1978); Lastein (1983); Leach (1975); Melchiorri-santolini & Hopton (1972); Verduin (1972) and Wetzel et al., (1972). The organic matter and carbon content of the sediment have been well documented (e.g. Carlton, 1984; Clay & Wilhm, 1979; Gorham & Sanger, 1967; Guppy & Happey-Wood, 1978; Storr et al., 1984). More integrated approach of energy flow studies from

phytoplankton through seston and sediment to benthic organisms are rare (Efford, 1969; Iwakuma et al; 1984; Jonasson, 1972, 1979, 1981; Kajak, 1972; Kajak & Rybak, 1966).

The Dubh Lochan was the subject for this project. It is a small dystrophic to oligotrophic freshwater lake situated near the eastern shore of Loch Lomond, on the Ross Peninsula. Previous studies on the lake have been concerned with the biology of Holopedium gibberum (Hamilton, 1958), dynamics of fish populations (Shafi, 1969), vertical migration of Chaoborus flavicans (Goldspink & Scott,1971), vegetation (Walker, 1975), energy flow from phytoplankton to zooplankton (Klarer, 1978), and a short term study on the quality and composition of seston (Millhouse, 1981).

The aim of the present study is to investigate the fate of photosynthetically fixed energy, part of which can directly go to zooplankton, some may join detritus to form mud at the bottom where some may be consumed by benthos and the rest may remain locked in to the sediment. In completing this aim, concentrations were given on phytoplankton and primary production, zooplankton (biomass), seston, sediment and benthos (biomass). As both phytoplankton and zooplankton play a major role in detritus formation (Saunders, 1980), it was necessary to determine

the patterns of seasonal succession of the two communities. In addition some important physical and chemical parameters were also examined to permit and understanding of the effects of these aspects of the environment on the bioenergetics of Dubh Lochan. Although Klarer (1978) studied plankton energetics and also the physico-chemical parameters in the lake, it was necessary to study them again because both ecological condition and plankton production could be very different after a 10 year period and there is also year to year variation in the dynamics of the parameters.

CHAPTER - 2.

DESCRIPTION OF THE STUDY AREA

2.1. General:

A lake can not be understood without proper knowledge of its catchment. The water owes much of its chemical properties to the geology, geography and cultural developement of the catchment. Climatic conditions also play an important role in the functioning of an ecosystem. Rainwater carries dissolved gases, ions, organic compounds and a wide variety of both organic and inorganic particles.

Air temperature (maximum and minimum), rainfall and sunshine data were collected from the Clyde River Purification Board (C.R.P.B.) station at Arrochymore, located approximately 6 km south of the Dubh Lochan (C.R.P.B. Annual Reports 1983, 1984 & 1985).

The Dubh Lochan (National grid reference NS 377964; Lat. 56° 7' N Long. 4° 35'W) lies approximately 7km north of the Highland Boundary Fault and about 8km from Balmaha near the eastern shore of Loch Lomond. It is separated from Loch Lomond by a small rise of about 200m (Goldspink & Scott, 1971).

Table 1. Meteorological data (1983 - 1984 and 1984 - 1985).

Months	1983 - 1984				1984 - 1985			
	Air temperature (°C)		Average rainfall (mm)	Average sunshine hrs./day	Air temperature (°C)		Average rainfall (mm)	Average sunshine hrs./day
	Max.	Min.			Max.	Min.		
October	18.1	-2.1	304.0	1.66	15.0	2.2	292.4	2.35
November	14.1	-5.2	49.6	0.75	14.0	-4.2	209.2	0.93
December	12.0	-2.6	265.2	0.75	12.1	-5.8	165.5	0.66
January	10.3	-9.7	274.3	0.85	10.2	-8.8	84.5	1.49
February	11.1	-6.2	125.0	1.42	10.5	-8.3	51.8	1.72
March	11.7	-6.1	85.1	1.87	11.4	-5.3	90.2	3.18
April	23.8	-3.6	64.0	4.57	15.8	-1.2	108.4	4.41
May	23.8	-0.9	21.8	5.98	20.4	-0.3	74.5	4.78
June	25.0	5.3	67.7	5.40	23.6	1.3	62.2	4.84
July	26.2	4.1	21.3	6.57	24.5	5.5	242.4	2.30
August	21.8	6.4	62.4	5.45	20.3	6.2	281.7	3.15
September	19.9	3.9	145.0	0.85	19.3	2.5	291.0	2.09

2.2. Geology :

The bedrock underlying the study area, lying in vertical bands, is a part of the Tay Nappe of the Dalradian series. Although there are controversies, it is believed that these sedimentary rocks were deposited during the pre - Cambrian or early Cambrian time in deep water (MacDonald, 1974). During the Caledonian orogeny of the Carboniferous period, they were metamorphosed into slates, grits and schists. The bedrock of the southern part of the basin is a band of grit and the northern part is a band of schists.

2.3. Climate :

Although the area is isolated from the open ocean, the climate of the study area resembles the Oceanic regime typical of the west coast of Britain except that the temperature range is more characteristic of inland rather than Oceanic Britain (Tittensor and Steele, 1971)

The monthly mean daily air temperature, rainfall and sunshine data from October, 1983 to September, 1985 are presented in Table 1. Weather conditions varied considerably between the two years. Rainfall and sunshine did not show predictable seasonal pattern (C.R.P.B. Annual Reports 1983, 1984 & 1985).

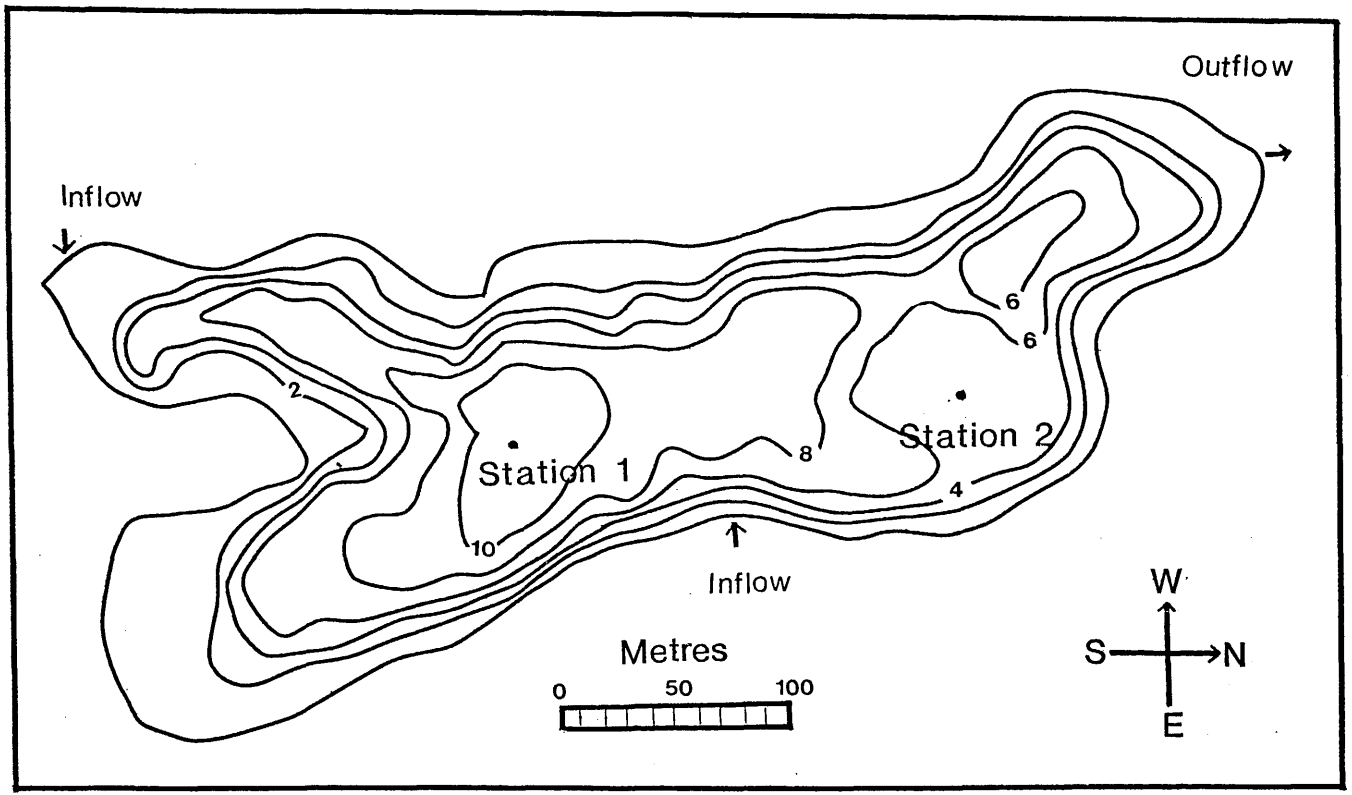
During 1983, mid autumn (October) was warm, very wet (rainfall = 304mm) and dull but the late autumn was moderately warm, dry but dull. The winter was very wet, dull and fairly cold (minimum air temperature = -9.7°C). The spring and summer of 1984 was exceptionally hot, dry and very sunny.

In 1984, the autumn was slightly colder, very wet and slightly more sunny than the previous year. The early spring of 1985 was slightly colder, wet and more sunny than the year before but the mid spring was very cold and wet. The early summer started moderately bright but from July onward it was comparatively colder than the previous year, very wet and dull. The rainfall from July to September this year was nearly 4 times more than that in the previous year (rainfall = 815.1mm).

Although the wind speed and direction data are very important in understanding the mixing process in the lake, they were not utilized because of the variations of local topography. However, the prevailing wind for the Loch Lomond area are from the south and west (Tittensor & Steele, 1971) and from those directions the Dubh Lochan is sheltered by high ground.

Figure 1. Morphometric map of Dubh Lochan showing locations of sampling sites (station 1 and station 2).

Morphometric map of Dubh Lochan



2.4. Vegetation of the catchment area :

The catchment area can be divided into three distinct vegetational regions although it is very small because of rugged terrain. The adjacent area surrounding the lake is dominated by a mixed oak (*Quercus petraea* Mattuscha Liebling), deciduous woodland (Tittensor & Steele, 1971). The vegetation of the northern area of the inflow stream is a pasture grass heathland (McVean, 1964). The vegetation of the northern area of the inflow stream and the north-eastern shore of the lake is a mixture of mainly Norway spruce (*Picea abies* L. Krast) and Japanese larch (*Larix kaempferi* Carriere) planted by the Forestry Commission in about 1954.

2.5. Dubh Lochan :

The lake lies on a NNW - SSE axis (Fig. 1). It has a surface area of 7.06 x $10^4 m^3$ and occupies a volume of 3.38 x $10^5 m^3$ (Table 2). There are two main inflows in to the lake. The principal stream flows in half way along eastern shore near the deepest part of the lake. It drains the neighbouring woodlands. Klarer (1978) reported that although the stream carries a lot of inflow, it does not contribute significantly to the nutrient level of the lake because the water is as nutrient poor as the lake itself. The other inflow is at the southern end of the

Table 2. Morphometry of Dubh Lochan.

Surface area	7.06 x 10^4	metre^2
Total volume	3.38 x 10^5	metre^2
Maximum depth	11.5	metres
Average depth	5.1	metres
Length	550.0	metres
Mean breadth	128.0	metres
Shoreline	1550.0	metres
Shoreline developement	1.645	
Volume developement	1.301	
Catchment area	1.1	kilometre^2

lake and carries seepage from the septic tank of the University Field Station. The water input is negligible but Klarer (1978) believed it to be potential source of nutrients to the lake. The present nutrient status of the lake (Figs. 14, 15, 16, 17 and 18) is very similar to that of Klarer's (1978) study which was conducted 10 years earlier. It is therefore, concluded that the nutrient input through this seepage has little effect on the lake. During periods of heavy rainfall many small rills also drain in to the lake. There is only one outflow at the north-western side of the lake which drains the lake water directly in to Loch Lomond. Other morphometric data are presented in Table 2. According to its nutrient status, it is classified as dystrophic to oligotrophic. The bottom of the lake is covered with very fine organic sediment of about 1m thickness and the shallow part is covered with sandy mud (Walker, 1975).

CHAPTER — 3.
ECOLOGY OF THE HABITAT

3.1. Introduction :

The dynamics of a freshwater ecosystem can only be understood properly in the context of its environment. Lakes are often classified on the basis of their physical (Whipple, 1898), chemical (Spence, 1967), or biological (Thienemann, 1925) properties. Solar radiation controls the temperature of the water, and the availability of light within the visible spectrum which provides energy to power photosynthesis. Temperature plays a major role in aquatic ecosystems especially in temperate regions because of the thermal stratification which may occur throughout the summer, and the freezing of the surface of the whole lake during the winter. The great seasonal variation of temperature and its related phenomena may be regulatory, inhibitory and lethal to the life in aquatic ecosystems. Brylinski and Mann (1973) reported positive correlations between the rate of photosynthesis and such features of the catchment as water chemistry and geographical location. Their ideas were based on data collected worldwide for the International Biological Programme (IBP). They concluded

that phytoplankton biomass is normally closely related to chemical factors like conductivity and phosphorus availability.

3.2. Materials and Methods :

3.2.1. General :

After a general survey of the Dubh Lochan during September 1983, two stations were selected for regular sampling (Fig. 1). Station 1 is located at the deepest part and is representative of the region of the lake where thermal stratification occurs throughout the summer and hypolimnetic oxygen depletion occurs during late summer. Station 2 is located at about 5m depth, still in a profundal zone, where temporary thermal stratification occurs occasionally during summer but no oxygen depletion occurs in the waters immediately above the sediment.

3.2.2. Physical :

Water levels were recorded every morning above an arbitrary base line.

Water temperature and dissolved oxygen (percentage saturation) were recorded at 1m intervals throughout the

water column on each sampling date at each station using a Mackereth combined thermister - oxygen meter. Both the thermister and the oxygen probe were calibrated in September 1983 and were checked and readjusted every month. Measurements were made at the same time of day between 10 and 11 A.M., to minimise the effect of diurnal variation.

3.2.3. Chemical :

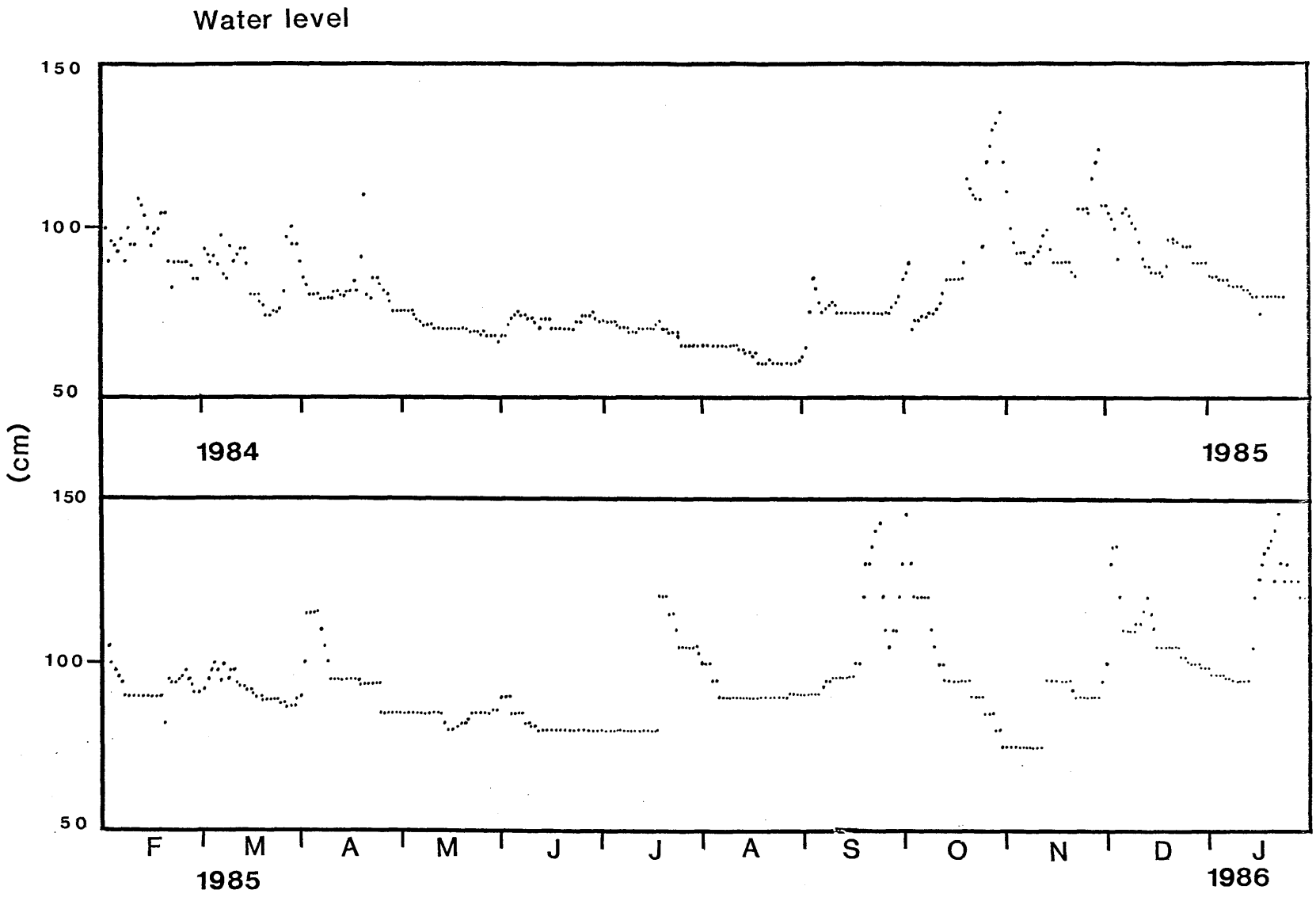
Water samples were collected using a 6l capacity Van Dorn water sampler from surface, 1,3,5 and 10m depth at station 1 and from surface, 1,3 and 5m depth at station 2. Samples were collected every fortnight from October 1983 to September 1985, except in January and February when they were collected once a month. It was possible to collect only one sample under ice cover, in January 1985. Each sample was used for chemical analysis and station 1 samples were also used for biological analysis. Samples were carried to the laboratory immediately after collection in 1l capacity polythene bottles, previously rinsed with sample water. They were filtered through GF/A paper to remove suspended matter. Chemical analyses were commenced within an hour of collection to minimise changes in water quality due to the exposure of the samples to the atmosphere and completed within 5 hours.

Hydrogen ion concentrations were measured with a Pye Unicam (Pye Model 292) pH/mV meter. Conductivity was measured with a Jenway (JP PCM 1) conductivity meter. Ammonia (μg NH4 - N/l) was determined according to Zadorojny et al., 1973. Alkalinity (bicarbonate), nitrate (μg NO3 - N/l) and silicate (reduction of silico molybdate) were measured according to Mackereth (1963). Orthophosphate (μg PO4 - P/l) and total dissolved organic carbon were measured according to Mackereth et al., (1978).

3.2.4. Biological (littoral and benthic communities) :

At the beginning of the study a general biological survey of the Dubh Lochan was undertaken. Littoral macrophytes were collected by hand, submerged and emegent plants including mosses with a plant hook, littoral invertebrates with a pond net and deep water benthos with an Eckman grab. Aquatic plants were identified according to Clapham et al., (1962) (vascular plants), Watson (1981) (mosses and liverworts). Benthos were identified according to Macan (1970) (Ephemeroptera). Hynes (1977) (Plecoptera), Hammond (1983) (Odonata), Hickin (1967) (Trichoptera), Macan (1976) (Hemiptera), Balfour-Browne (1950) (Coleoptera), Pinder (1978) (Diptera) and Kimmins (1940) (Megaloptera).

Figure 2. Daily water level fluctuations in Dubh Lochan from February, 1984 to January, 1986. Water level was recorded in centimetre from an arbitrary datum.


Water level
150
100
50
(cm)
1984
1985
150
100
50
F
M
A
M
J
J
A
S
O
N
D
J
1985
1986

3.3. Results and Discussion :

3.3.1. Physical :

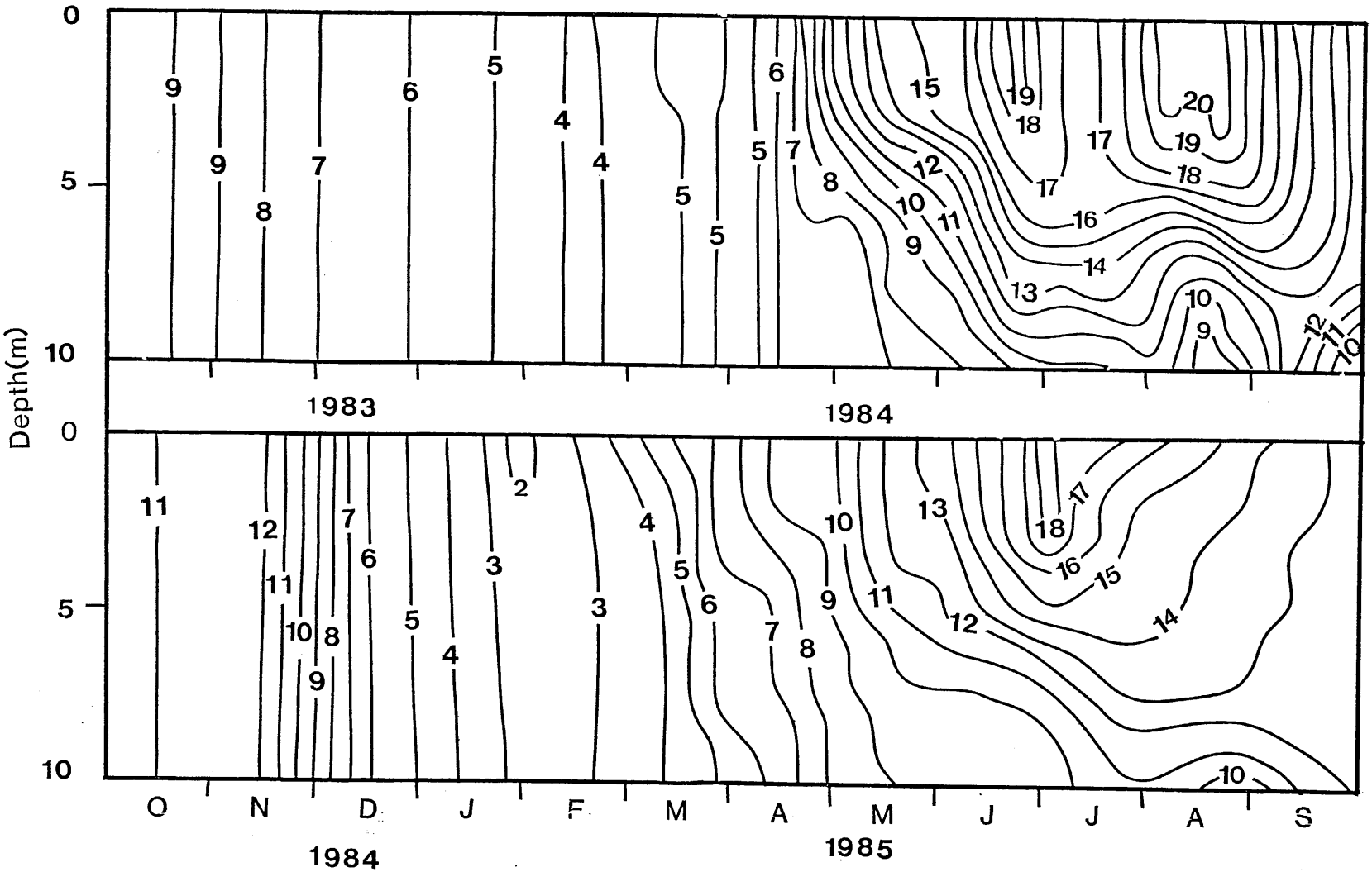
3.3.1.1. Water level :

Water levels varied from 60cm above arbitrary datum in August 1984 to 145cm in October 1985 with a maximum range of 85cm (Fig. 2). The highest water levels and more frequent fluctuations were generally observed during autumn and winter although the highest single daily change (45cm) was recorded in July 1985. Klarer (1978) also reported the greatest variations and highest water levels during autumn and winter. Although the water level data were not directly utilized in the study, they were helpful in determining the exact depth of placing the seston tubes and collecting water samples from just above the sediment.

3.3.1.2. Temperature :

The lowest temperature recorded at station 1 during the winter, 1984 was 3.75°C and the highest was 20°C in August (Fig. 3). In 1985 it varied from 1.5°C in January (under ice cover) to 18°C in early July. According to the thermal classification of lakes (Hutchinson, 1957), Dubh Lochan is a monomictic lake of the second order. At the start of

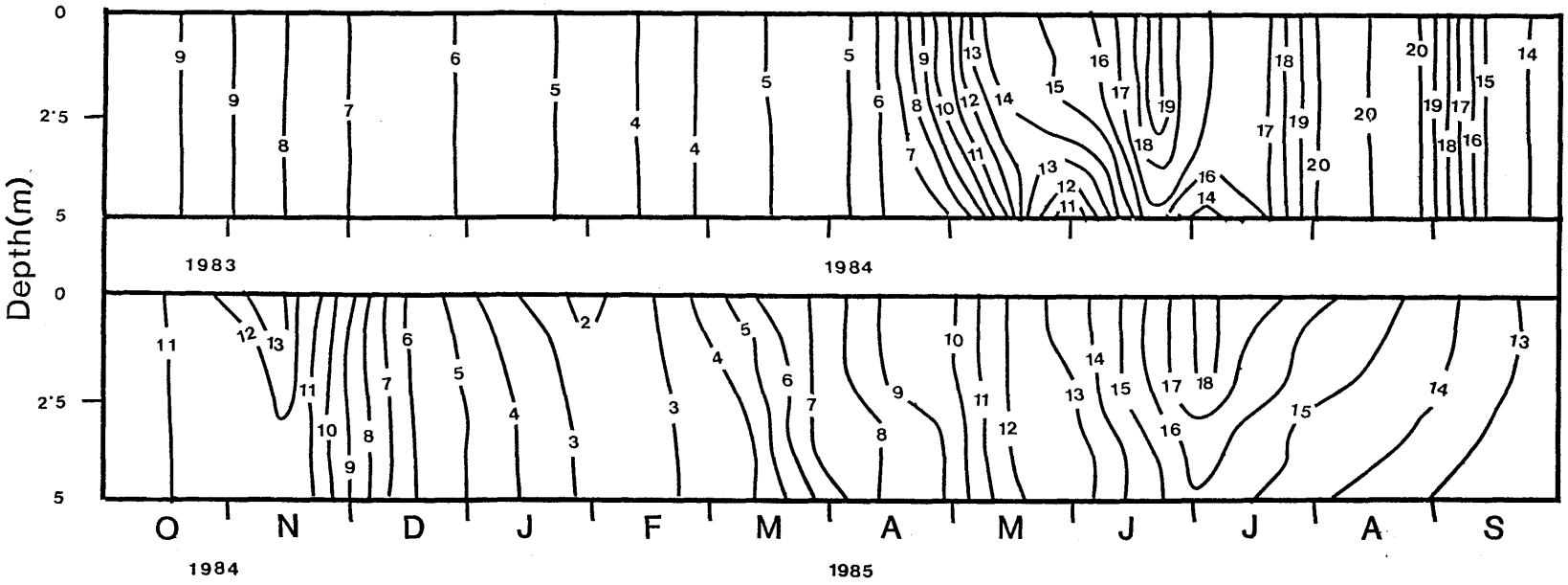
Figure 3. Seasonal variations of water temperature at station 1 from October, 1983 to September, 1985. Isopleths of water temperature are expressed in degree Celsius.


Water temperature - Station 1
Depth(m)
0
5
10
0
5
10
1983
1984
1984
1985
O
N
D
J
F
M
A
M
J
J
A
S

sampling in October, 1983, isothermal conditions prevailed at 9°C and cooling continued gradually until early February, when gradual heating commenced. Isothermal conditions continued until mid April when water temperature was 6°C. From that time surface water temperature increased progressively to 19°C by late June. Conditions remained isothermal through the surface 3m water. Evidence of thermal stratification was apparent at the end of April at 3 to 4m depth. By late June the epilimnion had extended down to 6m depth. From mid June to mid July there was a period of cooling in the epilimnion, followed by a rise in temperature to 20°C throughout most of August. During this period, the metalimnion extended from 4.5m depth. Throughout this time the temperature of the hypolimnion slowly increased to a maximum of 10°C at the end of July. Throughout September, progressive cooling of the epilimnion and slow warming of the hypolimnion lead to isothermal conditions again being resumed at 11°C in mid October. In the second sampling year, the isothermal conditions remained at 11°C until mid November, 1984, after which a rapid temperature drop occurred through to the end of January, when temporary inverse stratification was detected under ice cover. From February to the end of June a slow, more or less continuous increase in surface water temperature to 18°C occurred which was followed by a slow decline to 13°C by the end of sampling in September. Temperature conditions

Figure 4. Seasonal variations of water temperature at station 2 from October, 1983 to September, 1985. Isopleths of water temperature are expressed in degree Celsius.

Water temperature - Station 2



ceased to be isothermal with depth as early as mid March although a definite thermocline only became apparent from the end of May. The metalimnion was much less sharply defined than in the previous year, and was only apparent from the end of May at 5 to 6m depth until the end of July at about 8 to 9m depth. The deep water heating pattern was more or less similar to the previous year with the temperature rising to 10°C by late August.

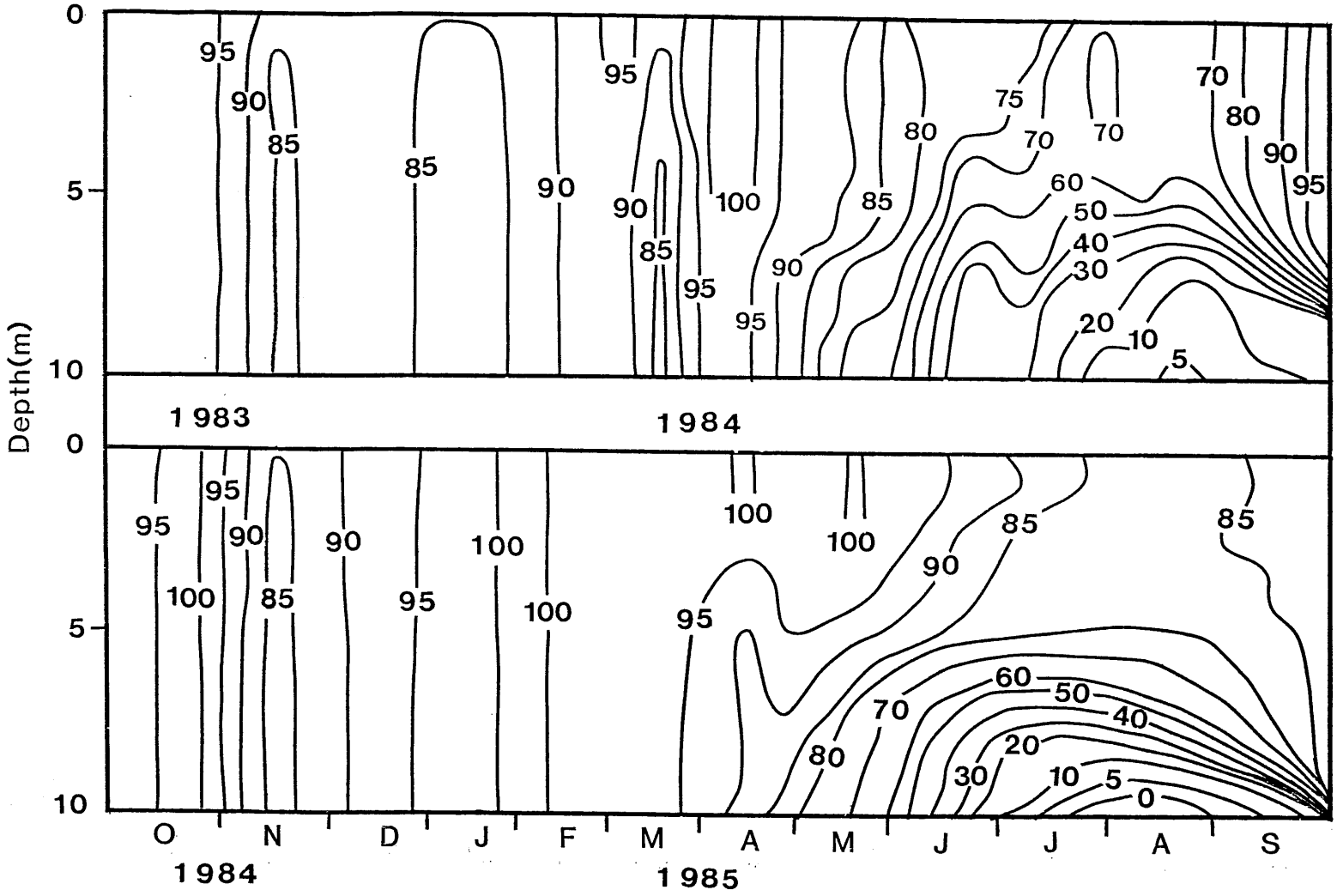
At station 2, surface water temperatures were similar to those at station 1 in both the years (Fig. 4), and isothermal conditions prevailed throughout most of the time, except for two periods of temporary stratification in late May and early July 1984.

The shallow parts of the lake were occasionally frozen between mid November and early January and on occasions between late February and late April. The surface of the whole lake was frozen from mid January to mid February in 1984. In the next winter the surface of the lake froze in mid November and then from mid January to late February.

Ice formation in Dubh Lochan was transitory (Klarer, 1978) and Goldspink and Scott (1971) reported it as intermittent. However it is probable that wind induced

Figure 5. Seasonal variations of dissolved oxygen at station 1 from October, 1983 to September, 1985. Isopleths of dissolved oxygen are expressed as percentage saturation.

Dissolved oxygen - Station 1



turbulance prevented winter stratification except under ice cover.

3.3.2. Chemical :

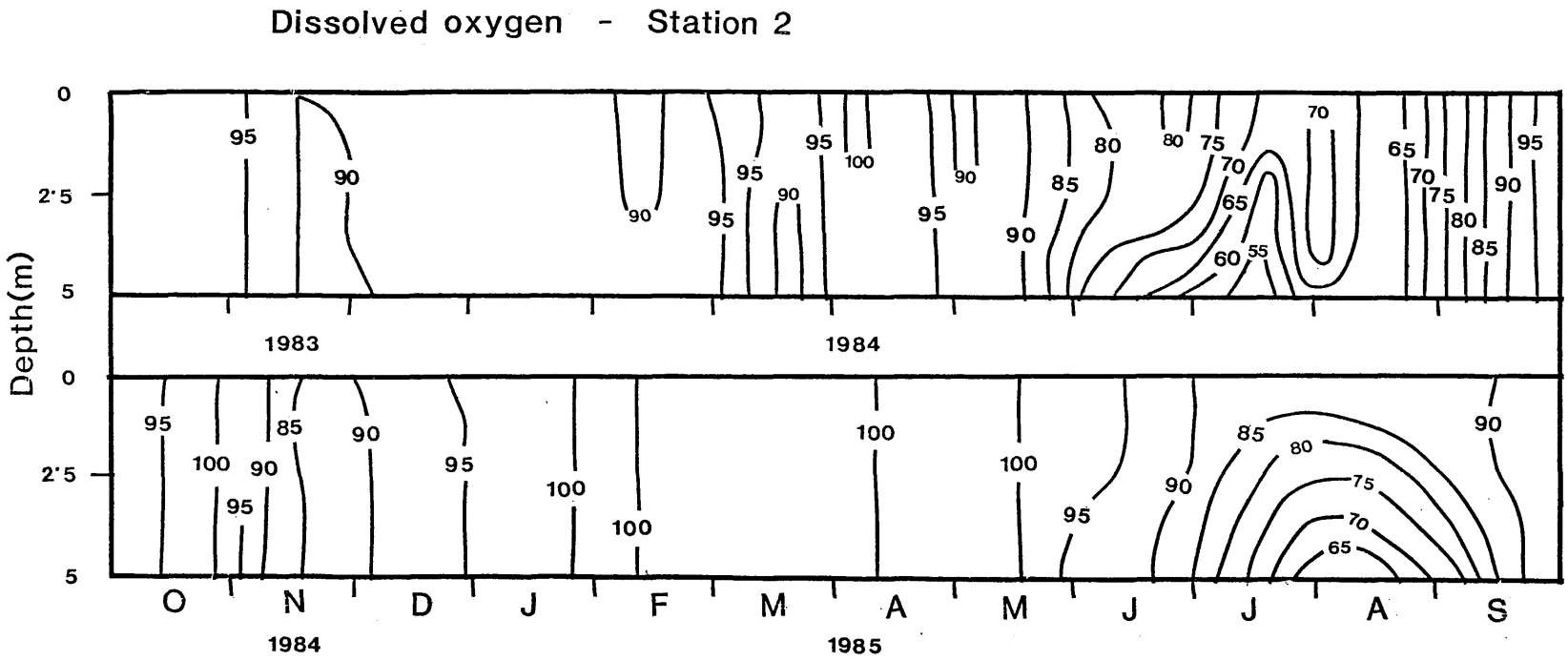
3.3.2.1. Dissolved oxygen :

Dissolved oxygen showed great seasonal and vertical distribution patterns. There were also differences between one year and another.

In deep water at station 1 (Fig. 5), oxygen saturation ranged from 85 to 100% throughout the water column during the isothermal period from October 1983 to late April 1984. From May, epilimentic oxygen declined gradually through the summer and reached 70% saturation by late July and August. In the metalimnion (4m depth) and hypolimnion, a progressive oxygen depletion occurred from late April through the summer and the hypolimnetic oxygen reached 5% saturation during late August. Oxygen stratification broke down very quickly during late September to early October resulting in complete mixing throughout the water column.

From October, 1984 to early April, 1985, oxygen levels remained more or less 100% saturation throughout the water column and continued through the epilimnion until late June.

Figure 6. Seasonal variations of dissolved oxygen at station 2 from October, 1983 to September, 1985. Isopleths of dissolved oxygen are expressed as percentage saturation.


Dissolved oxygen - Station 2
Depth(m)
0
2·5
5
0
2·5
5
1983
1984
1984
1985
O
N
D
J
F
M
A
M
J
J
A
S

From July to September, epilimnetic oxygen was about 85% saturation. In the metalimnion oxygen stratification started from late March which is a month earlier than the previous year. In the hypolimnion, oxygen saturation reached below detectable level from late July to August. This period of complete anoxic condition had a profound effect on the release of nutrients from the sediment. Oxygen stratification broke down comparatively quicker than the previous year resulting in complete mixing throughout the water column during late September.

In shallow water at station 2 (Fig. 6), the seasonal patterns of oxygen saturation was similar to the surface water at station 1. In the bottom waters, slight vertical stratification occurred in late June to July in 1984 and in mid July to mid August in 1985.

The lowest oxygen saturation at the bottom was 55% in 1984 and 65% in 1985. Stratification broke down quickly due to wind induced turbulance.

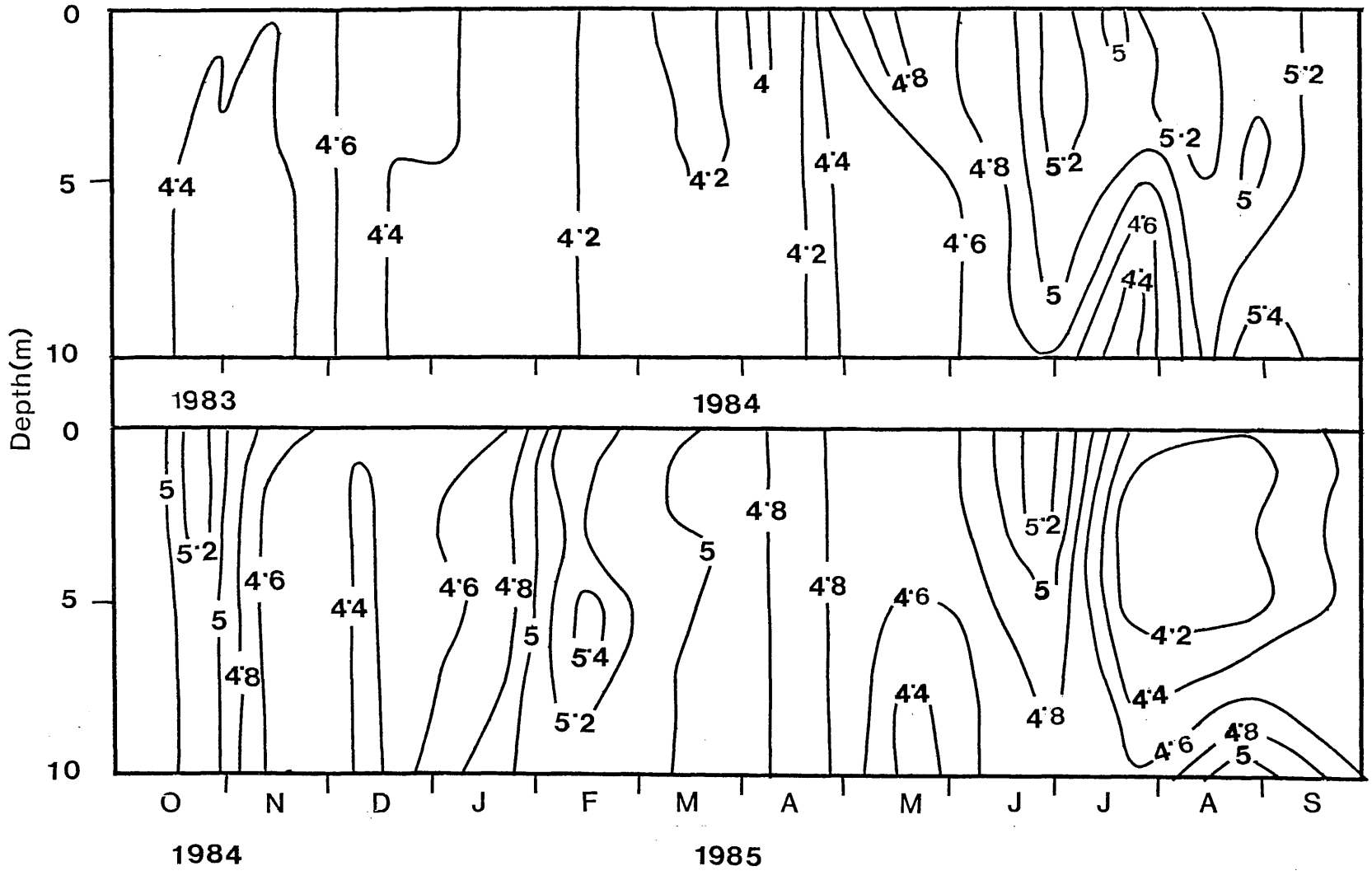
Dissolved oxygen is dependant on thermal conditions (Figs. 3 & 4). The lower levels of oxygen in the surface water during the late summer of 1984 seem to be related to the higher temperature than in the summer of 1985. However, during most of the time oxygen levels were close to

saturation which is generally observed in unproductive lakes such as Dubh Lochan due to low biological activity (Hutchinson, 1957). The rate of oxygen depletion below the metalimnion depends on the amount of oxygen present in relation to the amount of oxidizeable organic seston such as dead plankton, faeces and perhaps living plankton falling from the epilimnion metabolising its reserves or living saprobiotically (Hutchinson, 1957). The amount of organic seston (Chapter 7. Seston) sinking in Dubh Lochan is limited, so anoxic conditions are expected only when the epilimnion is large in comparison with the hypolimnion (Tressler, 1939). Klarer (1978) reported complete anoxia in the hypolimnion in 1974 and 1976, but not 1975. In this work it occurred in 1985 but not 1984. Both 1975 and 1984 were years in which isothermal conditions in the lake persisted beyond the second week in April, whereas in 1976 and 1985, evidence of stratification became apparent during the first two weeks of April. The time of commencement of stratification in the spring may be critical in determining whether or not complete anoxia develops in the hypolimnion later in the summer.

3.3.2.2. Hydrogen ion concentration (pH) :

Hydrogen ion concentrations showed distinct seasonal and vertical distribution patterns. It ranged from 4.0 to

Figure 7. Seasonal variations of hydrogen ion concentrations (pH) at station 1 from October, 1983 to September, 1985.

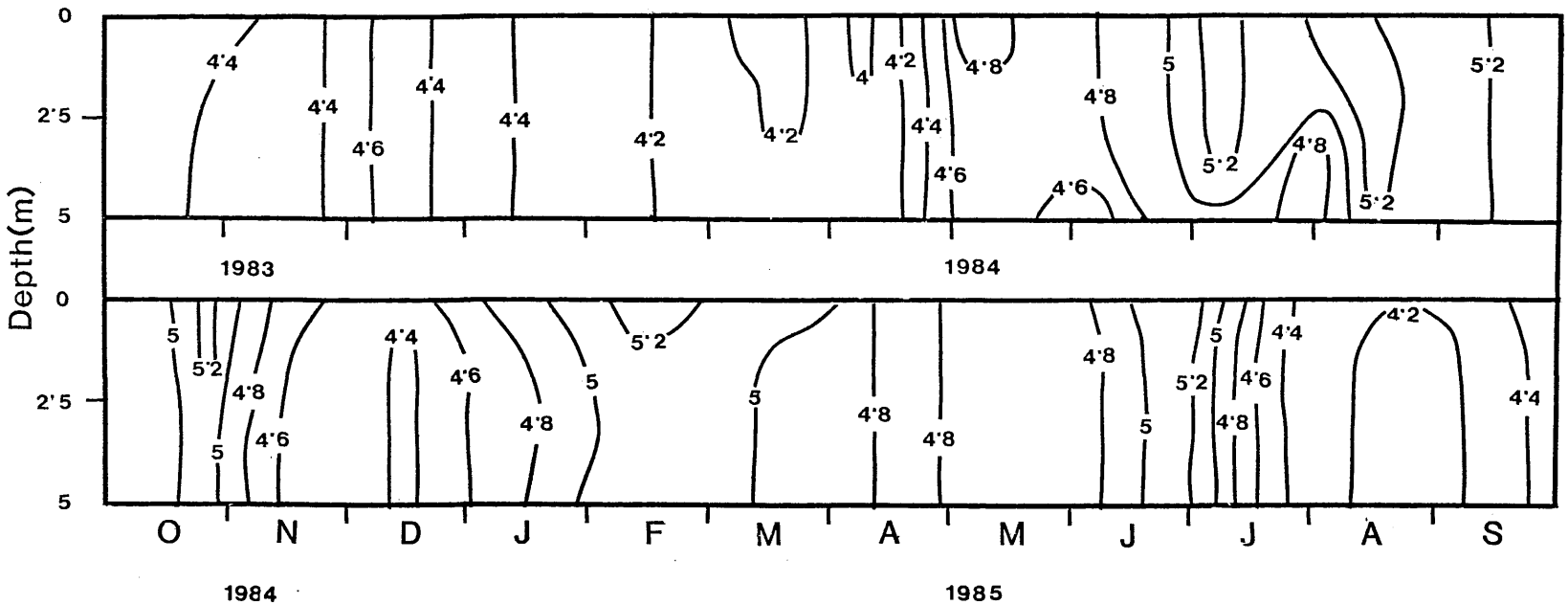

Hydrogen ion concentration - Station 1
Depth(m)
0
5
10
1983
1984
4·4
4·6
4·4
4·2
4·2
4
4·4
4·2
4·8
4·6
4·8
5·2
5
5
5·2
4·6
4·4
5·4
5·2
5
5·2
5
5·2
4·8
4·6
4·4
5
4·8
5
4·8
4·6
4·4
5·2
5
4·8
4·6
4·8
5
5·4
5·2
4·2
4·4
4·8
4·6
5
O
N
D
J
F
M
A
M
J
J
A
S
1984
1985

5.5 in 1984 and 4.2 to 5.4 in 1985.

At station 1 (Fig. 7) pH was almost uniform at about 4.2 from February, 1984 to mid April, over the previous three months there had been a slow decline to this level. From mid April onward the epilimnetic pH increased gradually to 5.2 and was maintained till the end of September and then declined gradually to 4.4 in December. During thermal stratification, pH increased slightly below the thermocline from 4.4 in early May to 4.8 in late June. It declined sharply and reached 4.4 in the hypolimnion in July and then increased to 5.5 in late August and mid September coinciding with the drop in oxygen concentrations to about 5% saturation. In 1985, the seasonal patterns of pH was very different from 1984. It increased gradually from January and reached a winter peak of 5.4 in mid February under ice cover. The summer rise in surface water started in the same way as in the previous year but was not maintained and declined from late June to early September at 4.2, a level which is reminiscent of winter conditions. During thermal stratification below the thermocline pH decreased from 4.8 in late April to 4.4 in late May and the hypolimnetic pH was about 4.6 up to late July. In anoxic condition in the hypolimnion, pH increased but to a lower level than in the previous year.

Figure 8. Seasonal variations of hydrogen ion concentrations (pH) at station 2 from October, 1983 to September, 1985.

Hydrogen ion concentration - Station 2



Slight vertical stratification of pH occurred in shallow water at station 2 (Fig. 8) during July and early August only in 1984 and the seasonal patterns were similar to the surface water at station 1. Hydrogen ion concentration appears to be greatly influenced by rainfall. From January to March, 1984, low pH (4.2) was associated with high rainfall (total rainfall for the period = 484.4mm), over the same period of time in 1985, high pH (5.4) was associated with low rainfall (total rainfall = 226.5mm). Although the winter pH peak in 1985 coincided with the period of ice cover, it is unlikely to be the cause because no pH rise was observed in the same period during the previous year. Conversely from July to September, 1984 high pH (5.2) in the surface water was associated with low rainfall (total rainfall = 228.7mm) at a time when the biological activity was minimum and low pH over the same period in 1985 was associated with high rainfall (total rainfall = 815mm). Problems of acid rain are causing increasing concern, particularly in the Highland regions of the country, such as Loch Lomond (Scottish Wildlife Trust, 1985 & Environmental Resources Ltd., 1983). Measurements of rain water quality from the Dubh Lochan catchment over the past two years have yielded pH values between 3 and 3.5 (David Brown, Pers. Comm.). These acid values may well account for the low pH in the lake and the situation is obviously one which merits further investigation.

The decline in pH in the metalimnion and hypolimnion in July, 1984 and from May to late July, 1985 is probably due to aerobic decomposition and subsequent production of free carbondioxide. The rise in pH in the hypolimnion during late August to early September in both the years under very low oxygen saturation (0 - 5%) indicate that the product of decomposition process are not free carbon dioxide. Mortimer (1941 - 1942) recorded similar decrease of pH in Esthwaite water in early summer (June) and a rise during late summer (September) in the hypolimnion during the period of low oxygen saturations.

Klarer (1978) reported seasonal patterns of pH in Dubh Lochan similar to 1984 but his values are on an average about 1 unit higher than in the present study.

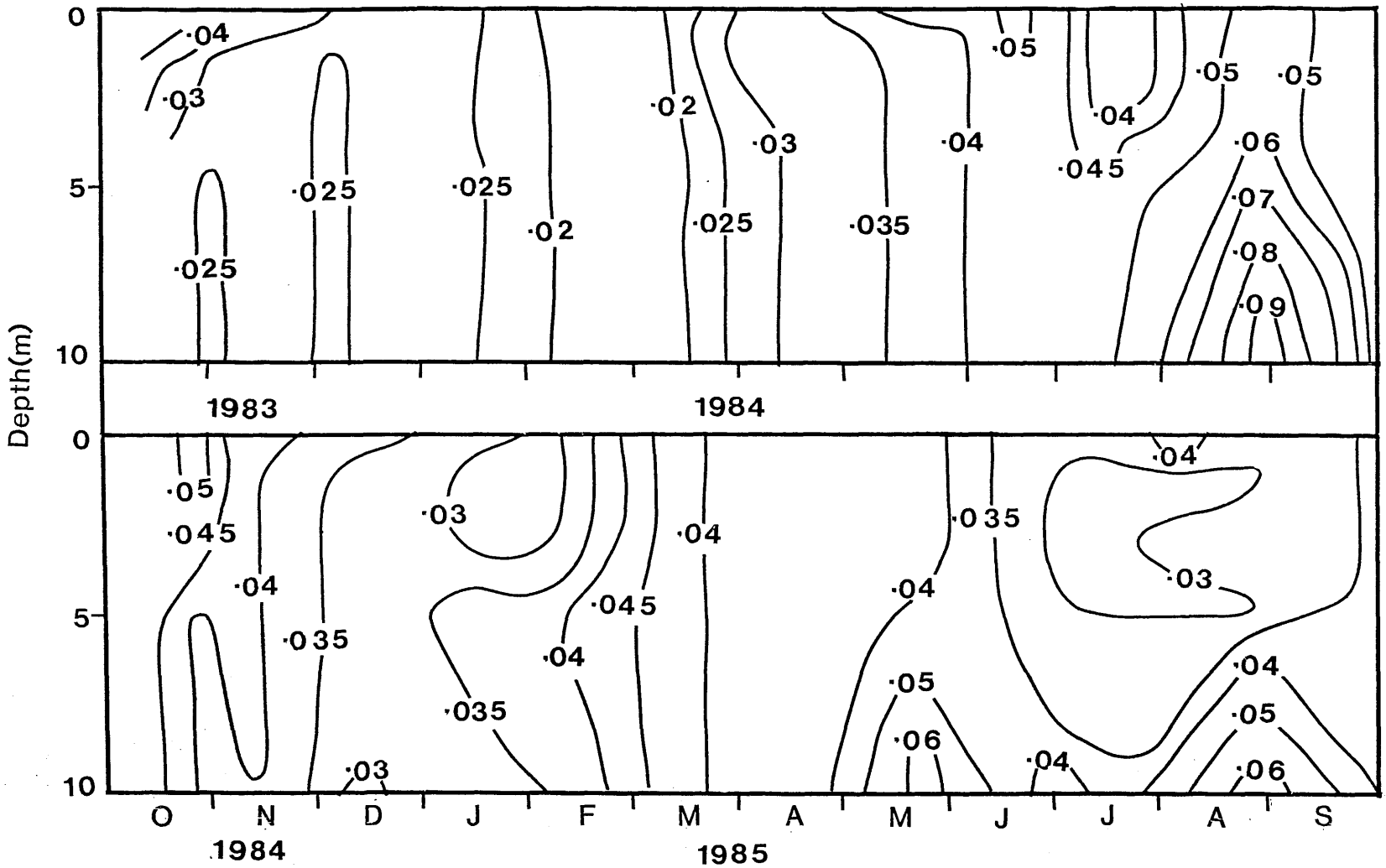
At this stage it is not possible to say whether the decline in pH over the past 10 years is real (acidification due to rain) or associated with the difficulties of measuring pH accurately in poorly buffered waters.

3.3.2.3. Alkalinity :

In most natural ecosystems, only some portions of the

Figure 9. Seasonal variations of alkalinity at station 1 from October, 1983 to September, 1985. Isopleyhs of alkalinity are expressed as bicarbonate mg/l.

Alkalinity - Station 1



bases (cations) are balanced by the acid anions. Alkalinity is an approximate measure of the amount of these excess bases combined with carbonate or more commonly bicarbonate. The immense importance of alkalinity lies in its role in carbon buffering system in natural ecosystems.

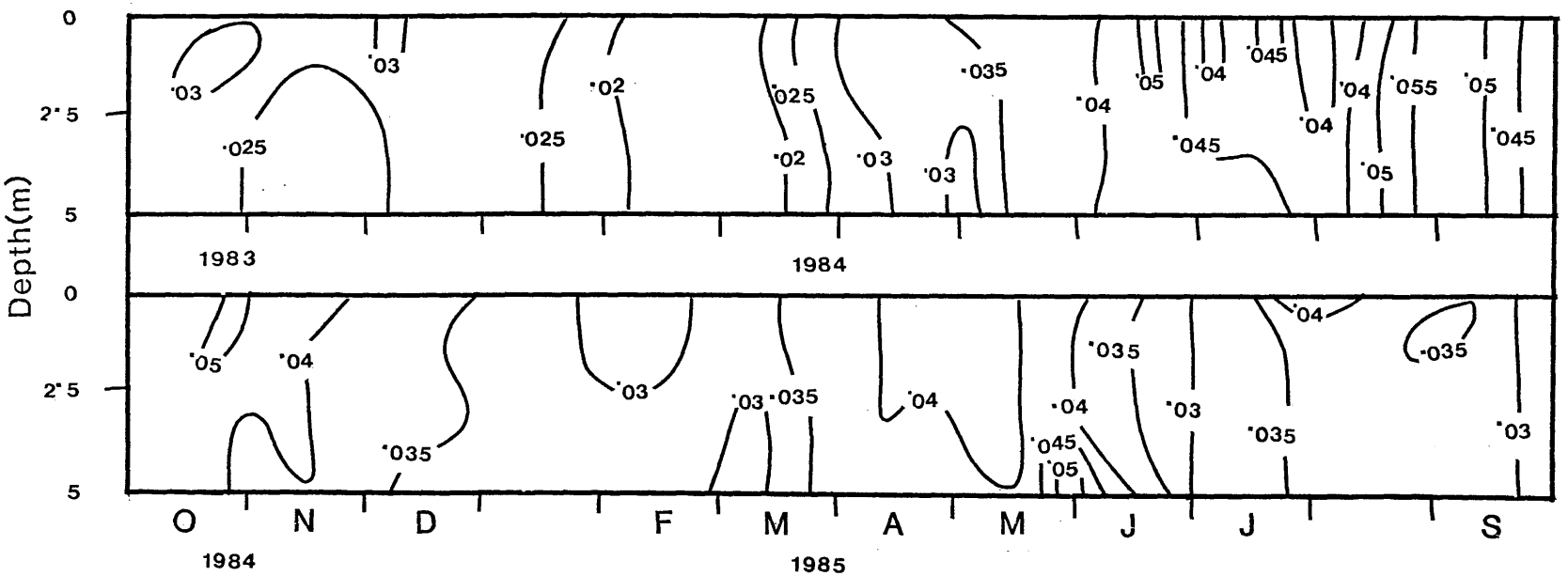
As expected alkalinity showed close correlation with pH in Dubh Lochan. It varied from 0.020meq/l to 0.095meq/l in 1984 and 0.030meq/l to 0.065meq/l in 1985.

At station 1 (Fig. 9), alkalinity levels were almost uniform at more or less 0.025meq/l from October, 1983 to mid January, 1984 and then declined to 0.020meq/l from late January to mid March with the decline of pH (Fig. 7). From late March alkalinity increased gradually throughout the water column up to early June. From mid June epilimnetic alkalinity increased slowly to 0.055meq/l in late August to early September and then declined throughout the water column to 0.030meq/l in December. Hypolimnetic alkalinity increased sharply from mid July and reached 0.095meq/l in late August to early September when the oxygen level was about 5% saturation (Fig. 5).

In 1985, the seasonal patterns of alkalinity was quite different and the levels were comparatively higher than the previous year except for the period from June to September.

Figure 10. Seasonal variations of alkalinity at station 2 from October, 1983 to September, 1985. Isopleths of alkalinity are expressed as bicarbonate mg/l.

Alkalinity - Station 2



It increased gradually from January and reached to 0.045meq/l in mid February to mid March with the rise of pH. In summer the epilimnetic alkalinity decreased to 0.030meq/l in July and August. In the hypolimnion alkalinity increased to 0.060meq/l in late May and then decreased slightly in late June to early July and then reached 0.065meq/l in late August to early September during anoxic condition. However, this peak was comparatively smaller than in the previous year.

In shallow water at station 2 (Fig. 10), no vertical stratification was observed although a slight tendency was noticed in July, 1984 and late May to early June in 1985 which was immediately broken by wind induced turbulance. However, the seasonal patterns were similar to the surface water at station 1.

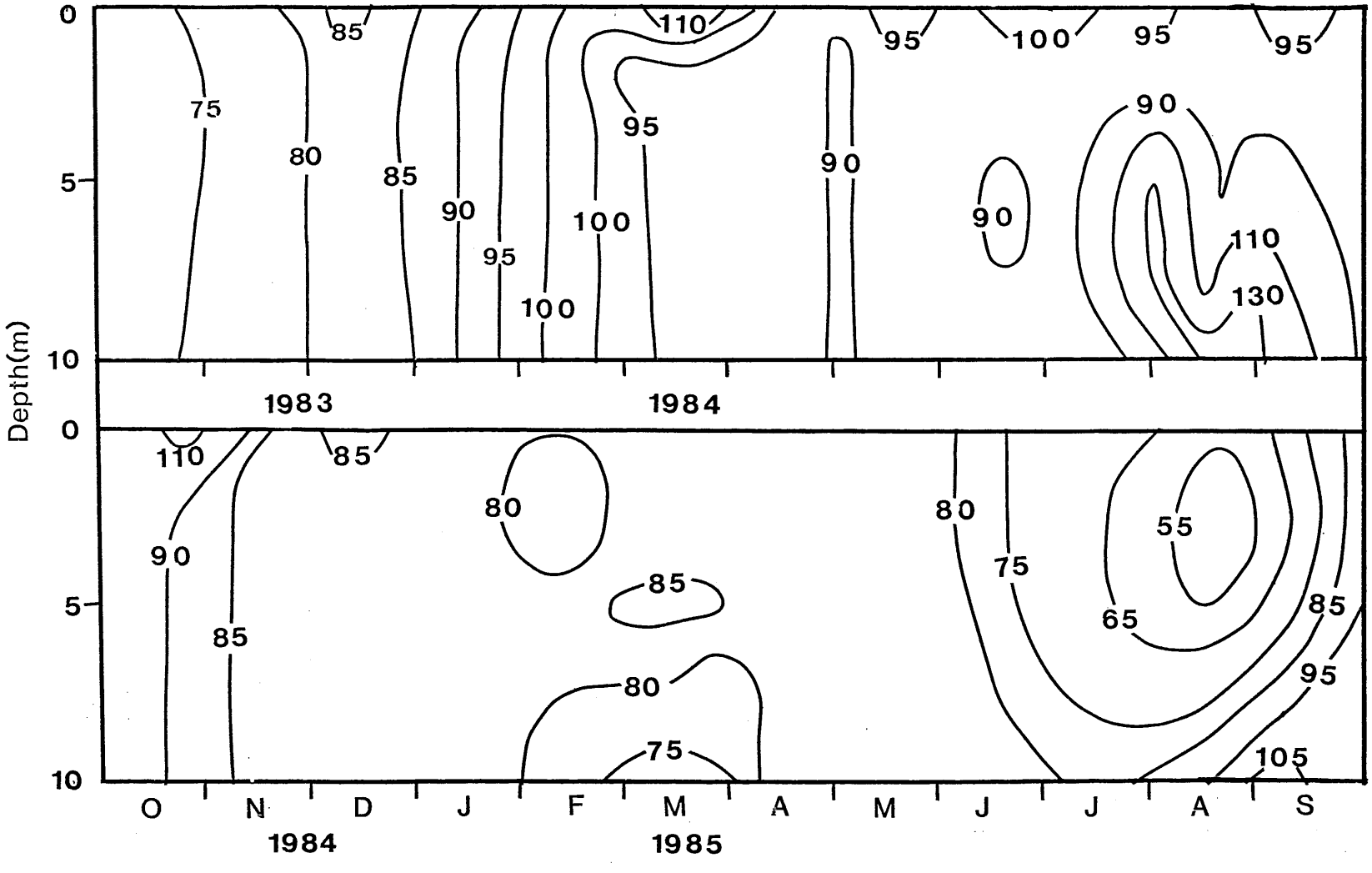
Low alkalinity from October, 1983 to March, 1984 and late June to late August, 1985 in the epilimnion could be related with low pH (Fig. 7) attributed by high rainfall. Hutchinson (1957) reported that below pH 5 free carbon dioxide and to a certain extent undissociated carbonic acid increases and very little bicarbonate is available in the water. The summer maximum in the epilimnion in 1984 and spring maximum in 1985 are related to increased biological activity and a shift in carbonate system towards bicarbonate

(Golterman, 1975) and higher pH unaffected by low rainfall. In May to early June, 1985, the increase in alkalinity in the bottom waters corresponding to a decline in pH is probably a result of aerobic decomposition and subsequent release of carbon dioxide. Increase in hypolimnetic alkalinity in anaerobic condition indicate that the product of decomposition processes are not free carbon dioxide. Instead these products may be any of a wide range of organic compounds (Golterman, 1975) which would not have been detected by the present method. The genesis of the increased bicarbonate concentrations in the hypolimnion during summer stagnation is very complex (Hutchinson, 1957). Mortimer (1941 - 1942) suggested that the rise of alkalinity in the hypolimnion could be due to the increase in ferrous iron (which was not determined in the present study), ammonia and possibly the presence of ferric hydroxide as well. Alkalinity data could not be compared with Klarer (1978) because he did not present alkalinity values.

3.3.2.4. Conductivity :

Conductivity is a complex measure of the total ionic status of water and is influenced both by biological activity and oxygen stratification.

Figure 11. Seasonal variations of conductivity at station 1 from October, 1983 to September, 1985. Isopleths of conductivity are expressed in micro Siemens/cm.


Conductivity - Station 1
Depth(m)
0
5
10
0
5
10
75
80
85
85
90
95
100
110
95
90
95
100
95
95
90
90
90
110
130
1983
1984
110
90
85
85
80
80
85
75
55
65
85
95
80
75
105
O
N
D
J
F
M
A
M
J
J
A
S
1984
1985

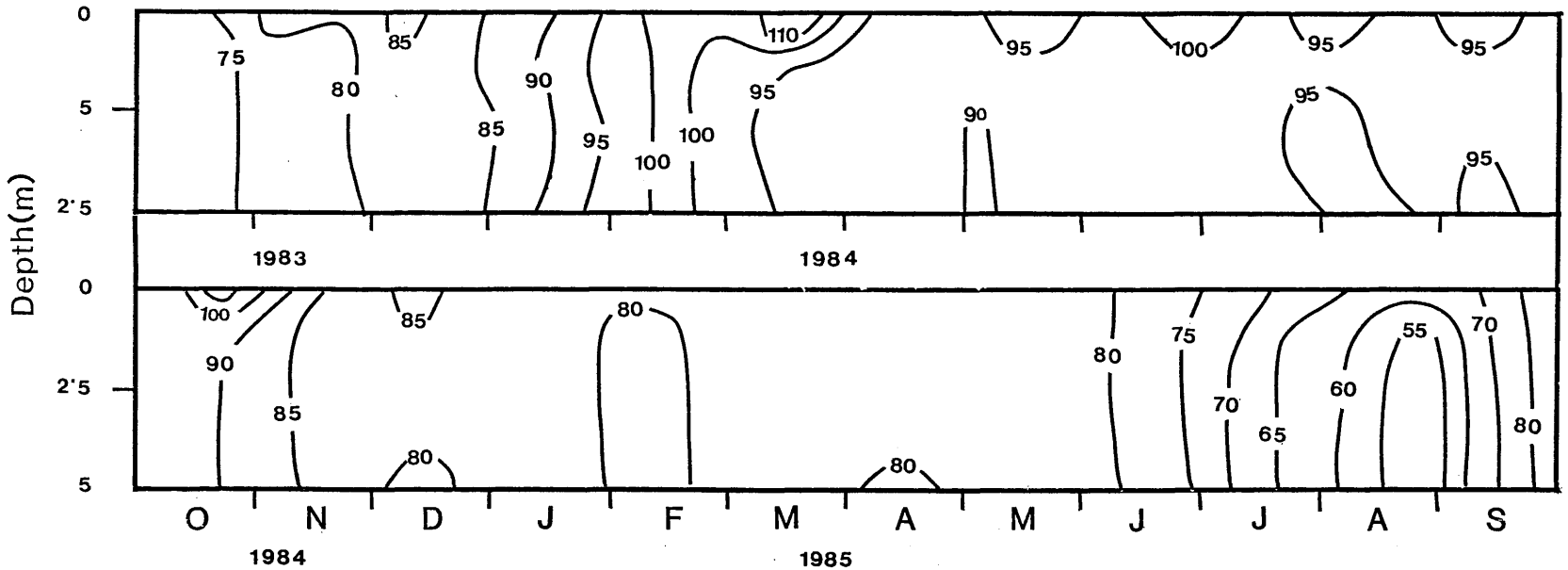
At station 1 (Fig. 11), conductivity gradually increased from 75 micro siemens/cm in October, 1983 to about 100 micro siemens/cm in February and early March, 1984. It declined slightly from April to early July throughout the water column to a level of about 90 micro siemens/cm and continued throughout the epilimnion during the whole summer. During thermal stratification, conductivity below thermocline increased gradually from mid July with declining oxygen saturation and reached to 131 micro siemens/cm in the hypolimnion in August and early September when the oxygen level dropped to 5% saturation. After autumn overturn and reintroduction of oxygen throughout the water column, conductivity returned to its pre - stratification level in October.

In 1985, conductivity levels were comparatively lower than the previous year. It was about 80 micro siemens/cm from January to mid June throughout the water column. During thermal stratification conductivity in the epilimnion declined slowly from 80 micro siemens/cm in June to 55 micro siemens/cm in August. In the hypolimnion, it increased slightly from late July and reached to 105 micro siemens/cm in late August to mid September in anoxic conditions.

At station 2 (Fig. 12), no vertical stratification in conductivity was observed and the seasonal patterns were

Figure 12. Seasonal variations of conductivity at station 2 from October, 1983 to September, 1985. Isopleths of conductivity are expressed in micro Siemens/cm.

Conductivity - Station 2



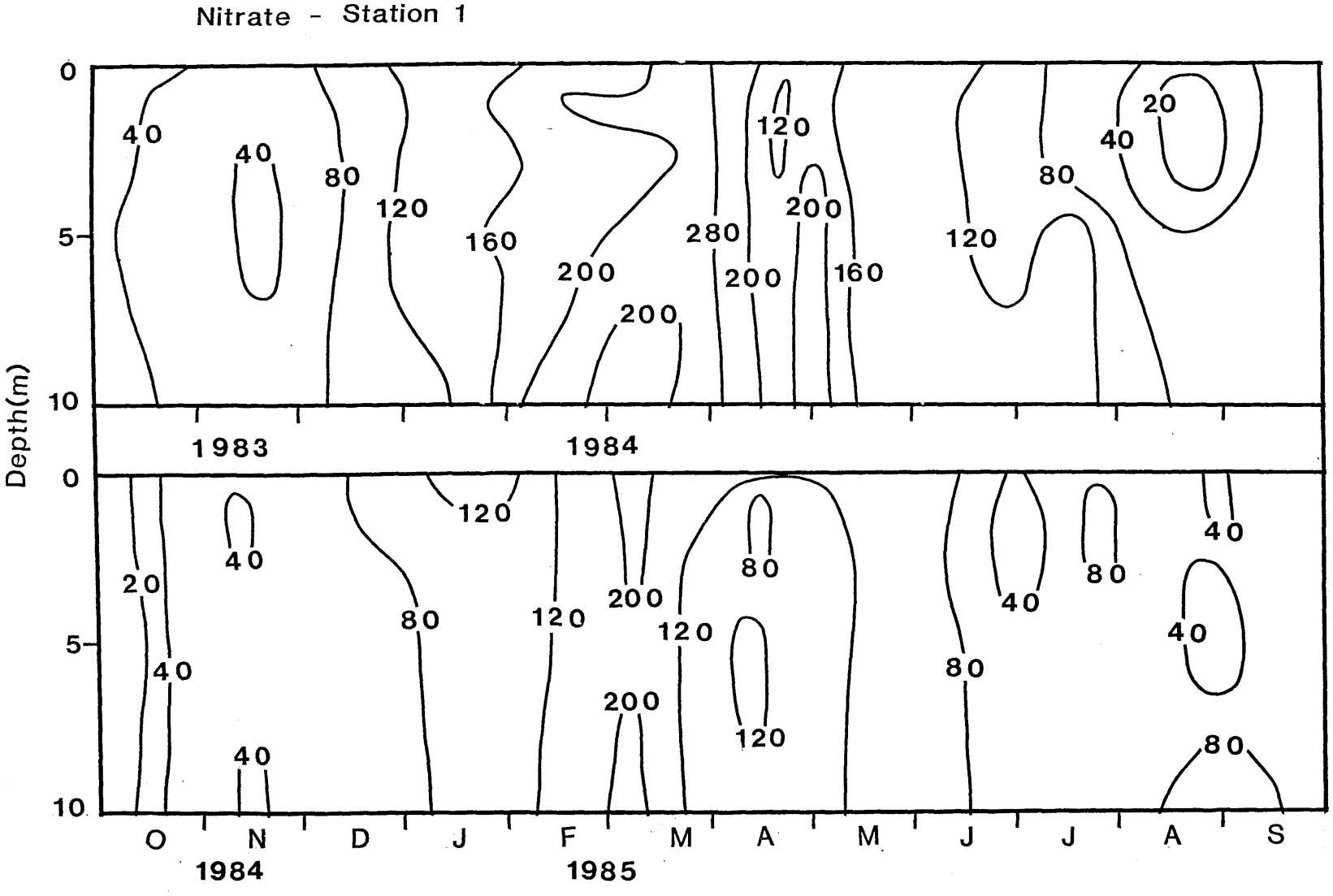
similar to the surface water at station 1.

Higher values of conductivity during winter months could be related to repressed biological activity (Moss, 1973). The rise in conductivity below the metalimnion coincides with high bicarbonate concentrations. Golterman & Kouwe (1980) reported that a strong correlation exists between conductivity and bicarbonate alkalinity. However, other ions e.g. Na, K, Ca, Mg, Fe, SO4. Cl etc., which were not measured in the present study are more important in determining the conductivity. Klarer (1978) reported very low conductivity (40 to 70 micro siemens/cm) in Dubh Lochan but the seasonal patterns were similar to the present study. Low conductivity in the epilimnion in 1985 could be related with low alkalinity and low pH due to unusually high rainfall during the summer.

3.3.2.5. Inorganic nitrogen :

The concentrations of inorganic nitrogen sources such as nitrate, nitrite and ammonia are generally low in most freshwaters and since they have great biological significance are often very important in determining the productivity of a given community (Reid, 1961). Among these three forms, nitrate, and ammonia were determined in the present study. Nitrite is normally present only as a

Figure 13. Seasonal variations of nitrate at station 1 from October, 1983 to September, 1985. Isopleths of nitrate are expressed in µg/l.


Nitrate - Station 1
Depth(m)
0
5
10
40
40
80
120
160
200
200
280
200
120
200
160
120
80
20
40
1983
1984
20
40
40
120
80
120
200
200
120
80
120
80
40
80
40
40
80
40
O
N
D
J
F
M
A
M
J
J
A
S
1984
1985

transitionary ion between the oxidized and fully reduced forms. The relative proportions of these ions in natural waters are primarily related to the oxygen concentrations. High oxygen concentrations favour nitrate and low concentrations favour ammonia (Mortimer, 1941-1942).

3.3.2.5.1. Nitrate :

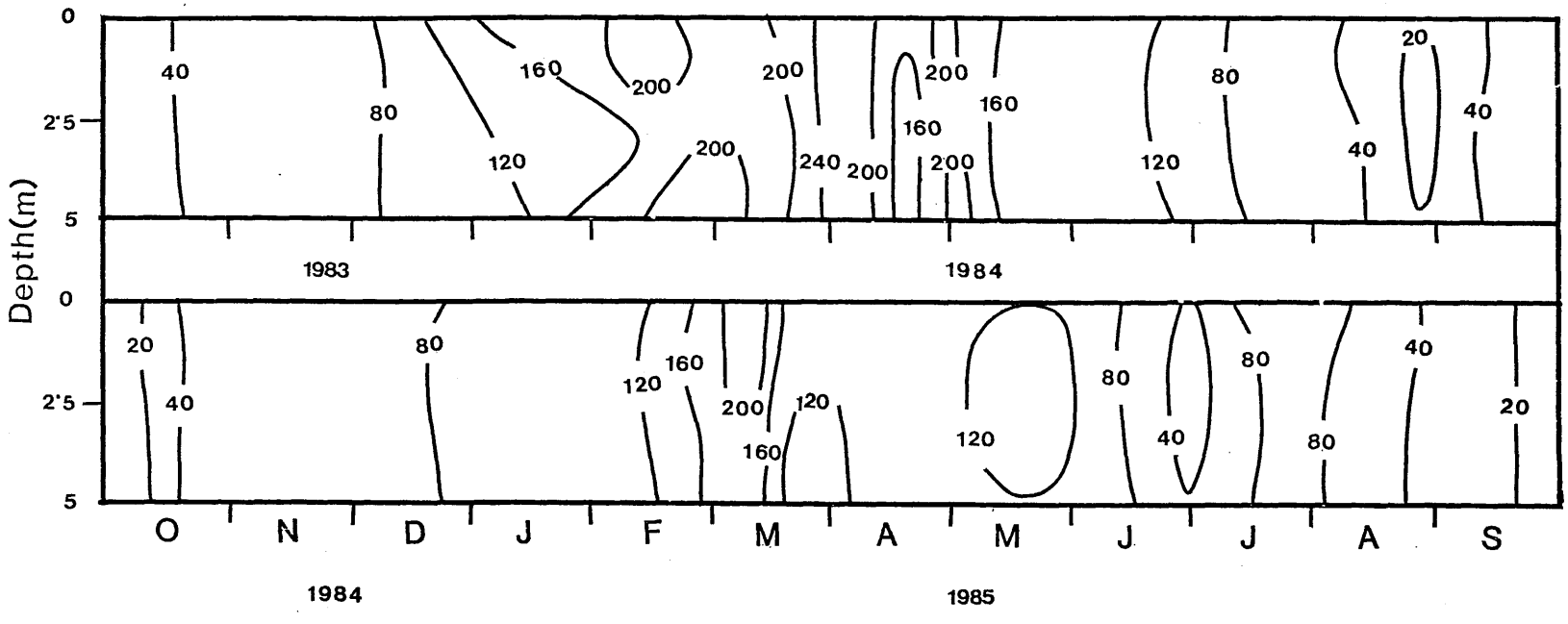
Nitrate concentrations showed great seasonal but no noticeable vertical distribution patterns. The concentration varied from 20µg/l to 280µg/l.

In deep water at station 1 (Fig. 13), the concentrations gradualllly increased from 40µg/l in October, 1983 to 280µg/l in late March and early April, 1984. From mid April, it declined sharply to 160µg/l in mid May. From then, it declined gradually through the summer and reached to 20µg/l in the epilimnion and about 60µg/l in the hypolimnion during late August and September. With the autumn overturn, the concentrations declined to about 20µg /l throughout the water column and then increased to about 40µg/l in November and December.

In 1985, the seasonal pattern was similar to the previous year. The highest concentrations reached to 200µg /l during late February and early March. The concentrations

Figure 14. Seasonal variations of nitrate at station 2 from October, 1983 to September, 1985. Isopleths of nitrate are expressed in µg/l.

Nitrate - Station 2



throughout the summer were slightly lower than in the previous year but in the hypolimnion it was slightly higher than in the previous year.

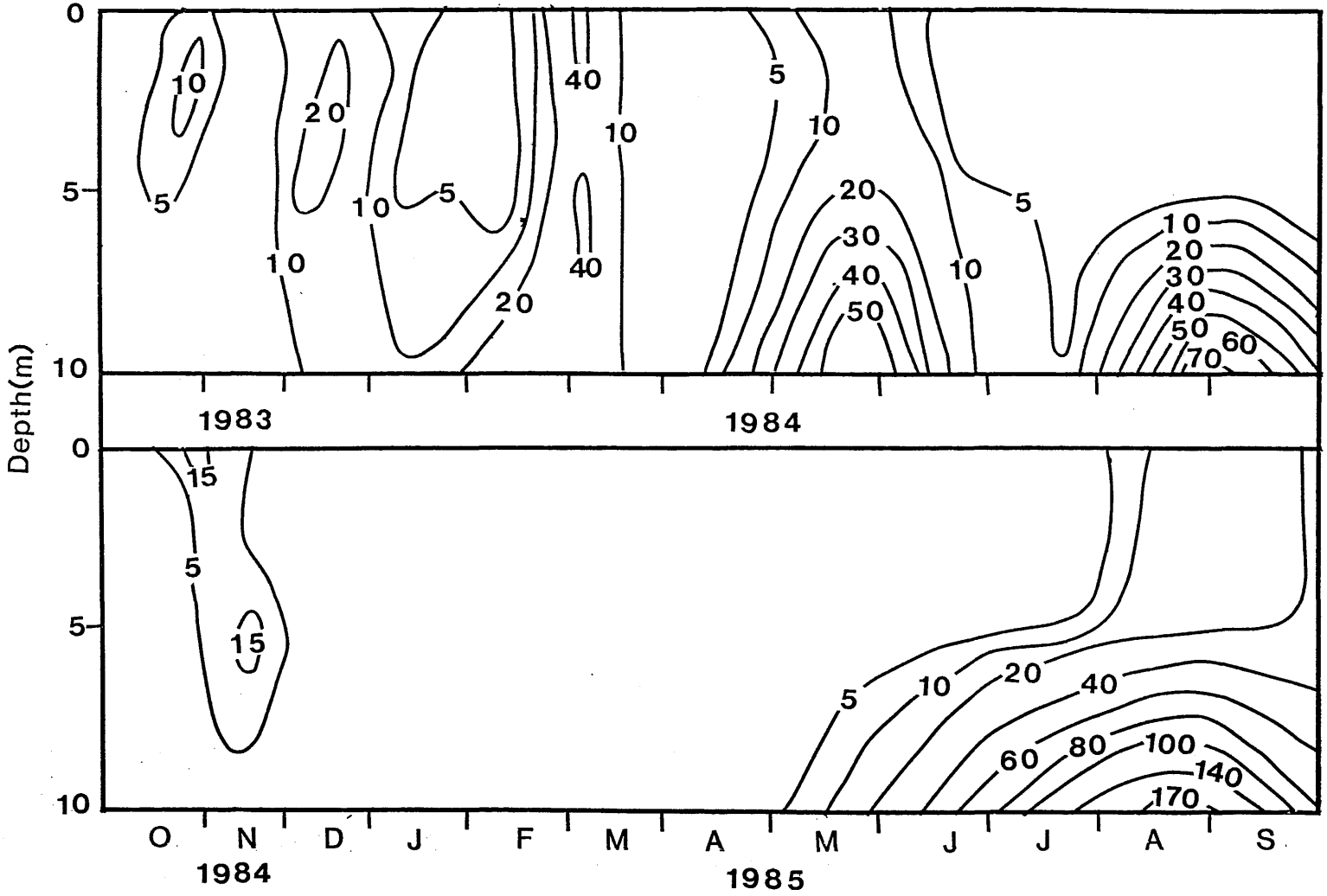
In shallow water at station 2 (Fig. 14), no vertical stratification was observed and the seasonal distribution patterns were similar to the surface water at station 1.

Klarer (1978) reported similar patterns of seasonal variation of nitrate in Dubh Lochan but his values were always lower than the present study (maximum concentration = 120µg/l).

The highest level of nitrate during late winter and early spring could be related to minimal biological actiivity (Moss, 1973) and maximum inflow. Golterman (1975) reported that surface runoff and rainfall could be the important sources of nitrate in lakes. The lowest concentrations in the epilimnion during August and September could be mainly due to assimilation by algae. (Mortimer, 1941-42). Unlike ammonia, nitrate concentrations did not show noticeable vertical stratification during the summer stagnation period. However, the concentrations were slightly higher in the hypolimnion than the rest of the water column in Dubh Lochan. Reid (1961) reported that there is some evidence of nitrate stratification in oligotrophic

Figure 15. Seasonal variations of ammonia at station 1 from October, 1983 to September, 1985. Isopleths of ammonia are expressed in µg/1.

Ammonia - Station 1



lakes where epilimnetic nitrate is reduced by phytoplankton and little change occurs in deep water, and this is true in the present study. Most workers (Hutchinson, 1957; Mortimer, 1941-42; Schindler & Comita, 1972) reported a rapid reduction of nitrate in the hypolimnion with the depletion of oxygen during summer stagnation. However in the present study, the small build up of ammonia (Fig. 15) in the hypolimnion during summer stagnation in 1984 and the large build up during the same period in 1985 seem to be derived from the sediment rather than from nitrate reduction.

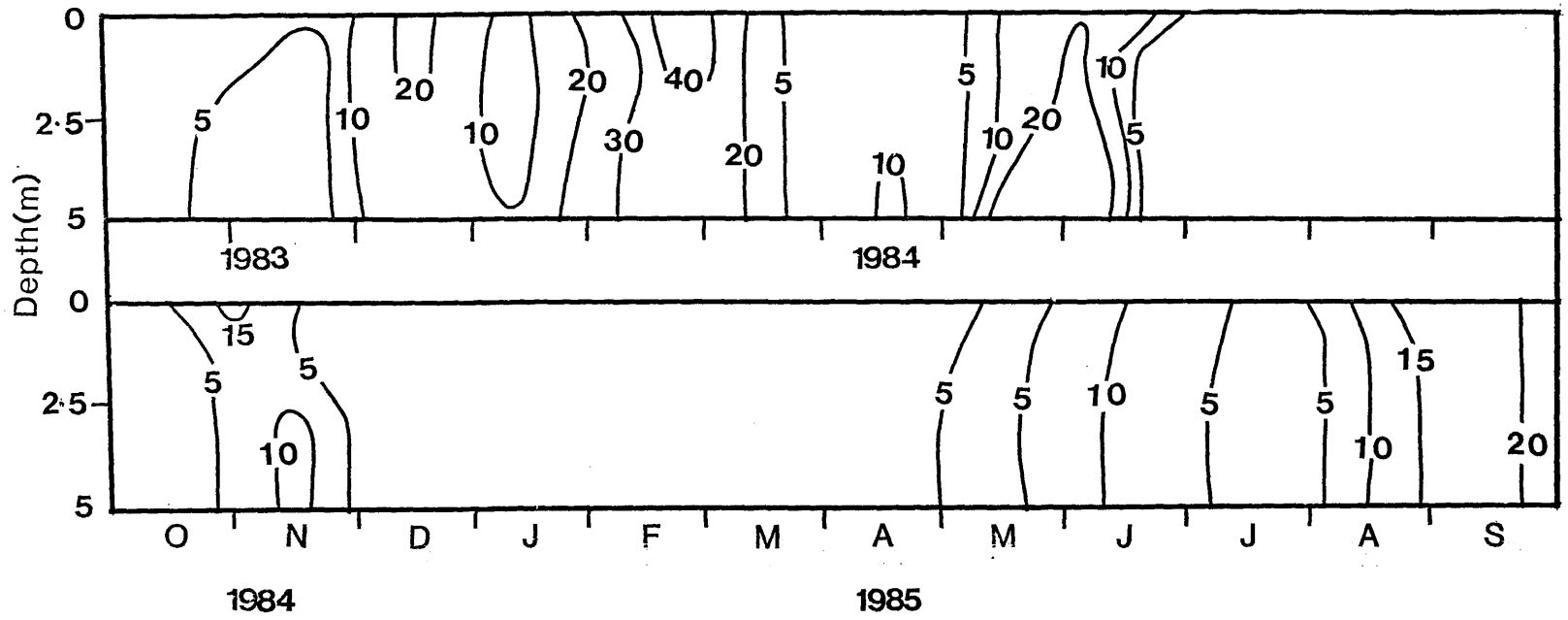
3.3.2.5.2. Ammonia :

Ammonia concentrations showed distinct seasonal and vertical distribution patterns. Considerable variation was also observed between the two years.

In deep water at station 1, the concentrations remained between 5 and 10µg/l from October, 1983 to January, 1984 in the deep part of the lake (Fig. 15). It increased gradually to about 40µg/l during late February and early March and then declined sharply to less than 5µg/l in late March and early April. From mid April to mid June, the concentrations in the upper waters remained between 5 and 10µg/l and then declined to undetectable level from mid June to early

Figure 16. Seasonal variations of ammonia at station 2 from October, 1983 to September, 1985. Isopleths of ammonia are expressed in µg/l.

Ammonia - Station 2



October. After an increase to about 15µg/l in November, it became undetectable in December. The concentrations in the bottom waters increased gradually from mid April and reached to 50µg/l in late May to early June and then declined gradually to 5µg/l in early July. The concentrations below the thermocline increased gradually from late July with declining oxygen saturation and reached to 75µg/l in the hypolimnion in late August and early September. With autumn overturn and reintroduction of oxygen, the concentrations declined to its pre - stralification level throughout the water column.

In 1985, ammonia concentrations remained below undetectable level throughout the water column from January to April and continued throughout the epilimnion to mid July. From late July, the concentrations in the epilimnion increased slightly to about 20µg/l in late September. The concentrations below the thermocline increased gradually from mid May with declining oxygen saturation and reached to 170µg/l in the hypolimnion during late August and early September when the sediment surface was completely deoxygenated.

In shallow water at station 2 (Fig. 16), ammonia concentrations did not show vertical stratification and the seasonal patterns were similar to the surface waters at

station 1.

In Dubh Lochan, Klarer (1978) observed 200µg/l ammonia in the hypolimnion during late August and early September, 1974 when the oxygen saturation was about 5% and about 400µg/l in the same period in 1975 when the hypolimnion was completely deoxygenated. Starting from comparatively higher concentrations of ammonia in 1984 than 1985, a hypolimnetic increase started with the developement of thermal stratification at the end of April. In the second year, ammonia was almost undetectable for the 5 winter months, so the hypolimnetic increase was slow to get underway. However, there is evidence that there was no mixing between surface water and those immediately above the sediment in 1985 after mid March, oxygen depletion in the hypolimnion had longer to develop than in the previous year, and under these progressively more reducing conditions, ammonia was released from the sediment to a greater degree than the previous year.

Mortimer (1941-1942) suggested that the increase of ammonia in oxidized condition in the hypolimnion during summer stagnation was primarily due to the reduction of nitrate and in reduced condition rapid increase in ammonia would be due to the release from the sediment. In the present study, nitrate concentration (Fig. 13) also

increased slightly in the hypolimnion during summer stagnation, so it is unlikely that the increase in ammonia during early summer was due to the reduction of nitrate.

Ammonia is the major excretaery product of zooplankton and other aquatic animals (Winberg, 1971). The sources of this gradual increase of ammonia during early summer could be aerobic decomposition of organic matter and the animal excretion.

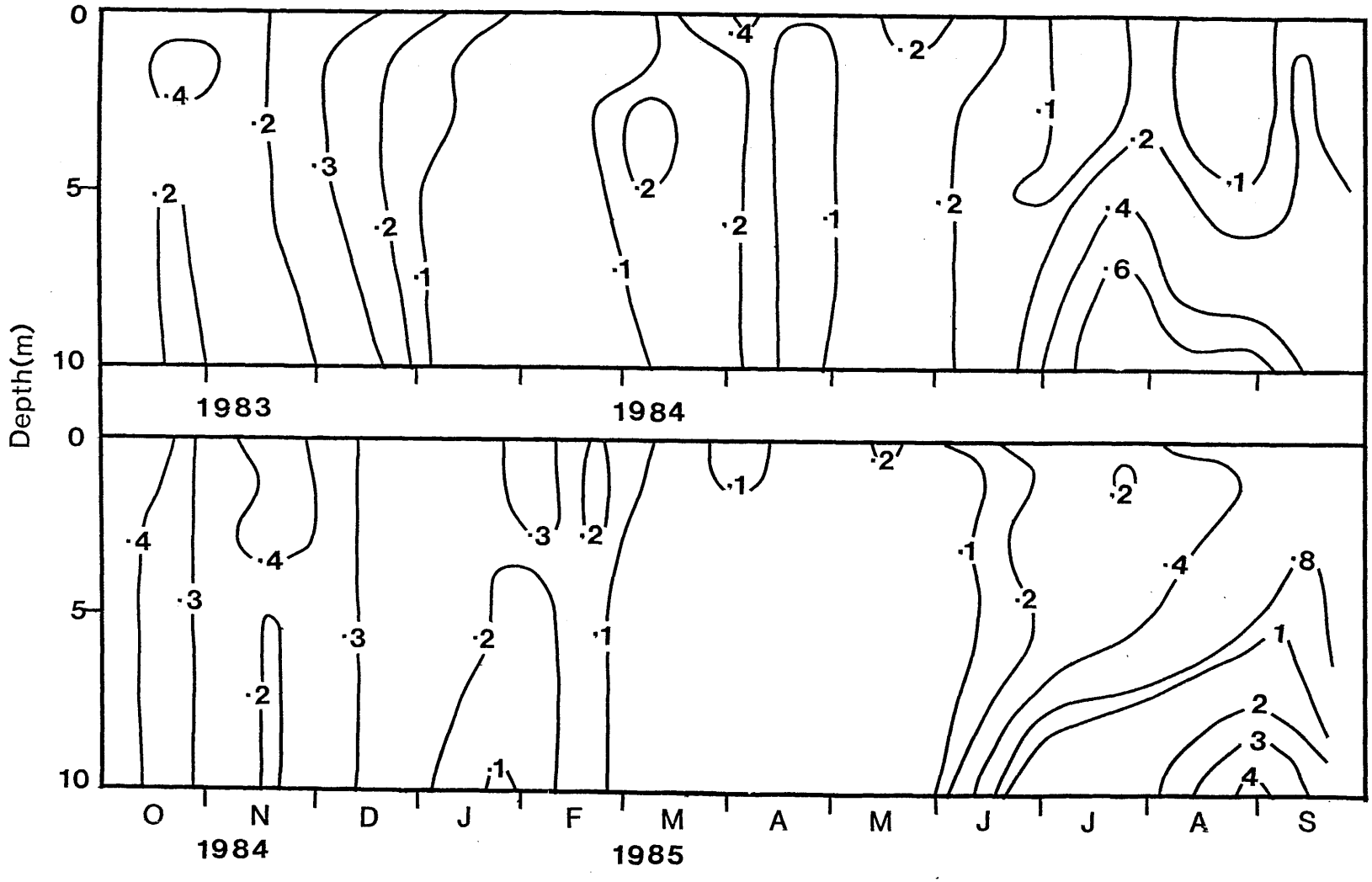
After the autumn overturn, ammonia concentrations declined to pre - stratification levels throughout the water column. Nitrate concentrations also did not increase with the decline of ammonia. It was therefore, concluded that most of the ammonia produced in the hypolimnion during summer stagnation was again trapped in the sediment (Mortimer, 1941-1942).

3.3.2.6. Orthophosphate :

Ecologically phosphorus is often considered the most critical single factor in the maintanence of biochemical cycles. It is an essential element in the energy transfer systems of the cells. The deficency of phosphorus could lead

Figure 17. Seasonal variations of orthophosphate at station 1 from October, 1983 to September, 1985. Isopleths of orthophosphate are expressed in µg/l.

Orthophosphate - Station 1



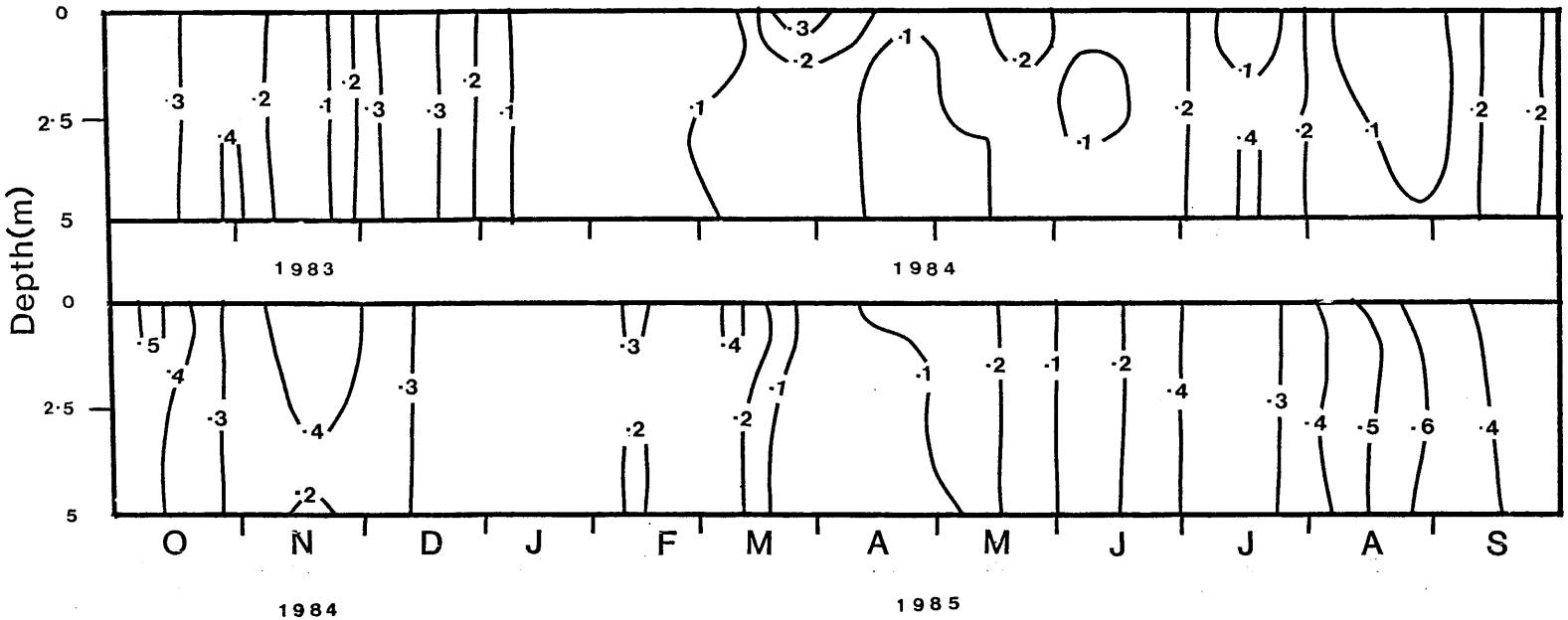
to inhibition of phytoplankton growth, resulting decline in the productivity in aquatic ecosystems (Reid, 1961). Because of its relative insolubility, it is normally available from the environment in very small quantities compared to other nutrients in relation to demand so often limiting. The luxury uptake of phosphorus is well documented for phytoplankton (Moss, 1982) which can enable algae to grow in waters where one would otherwise expect production to be limited by phosphorus availability.

Orthophosphate concentrations in Dubh Lochan were always very low, ranging from undetectable level to a maximum of 4µg/l.

In deep water at station 1 (Fig. 17), the concentrations in the surface water was about 0.4µg/l and slightly lower in the bottom water in October, 1983. It declined gradually from November and reached to 0.1µg/l during January and February, 1984. The concentrations increased slightly in March and reached to 0.4µg/l in the surface water in early April. From mid April to early June, the concentrations remained at about 0.1µg/l throughout the water column. During thermal stratification, phosphate concentrations in the epilimnion remained at about 0.1µg/l from late June to early September, but in the hypolimnion, it increased to about 0.6µg/l from mid July to early September. After the autumn overturn, it increased to about

Figure 18. Seasonal variations of orthophosphate at station 2 from October, 1983 to September, 1985. Isopleths of orthophosphate are expressed in µg/l.

Orthophosphate - Station 2



0.4µg/l throughout the water column from October to early December.

In 1985, the concentrations during the winter was slightly higher than the previous year. From March to May, in the upper 1m water it was about 0.1µg/l and was below detectable level in the rest of the water column. During thermal stratification, it increased slightly in the epilimnion and reached to 0.4µg/l in August and September. In the hypolimnion, the concentrations increased gradually from late June with declining oxygen saturation and reached to 4µg/l in late August and early September when the hypolimnion was completely deoxygenated. In shallow water at station 2 (Fig.18), orthophosphate concentrations did not show vertical stratification and the seasonal patterns were similar to the surface waters at station 1.

Klarer (1978) reported comparatively higher concentrations of orthophosphate than the present study in Dubh Lochan, ranging between less than 1µg/l during most of the time throughout the water column to 20µg/l in February. He attributed this later result to contamination by motor oil through the inflow water. However, low values of orthophosphate similar to the present study was reported by Maulood & Boney (1980) in Loch Lomond.

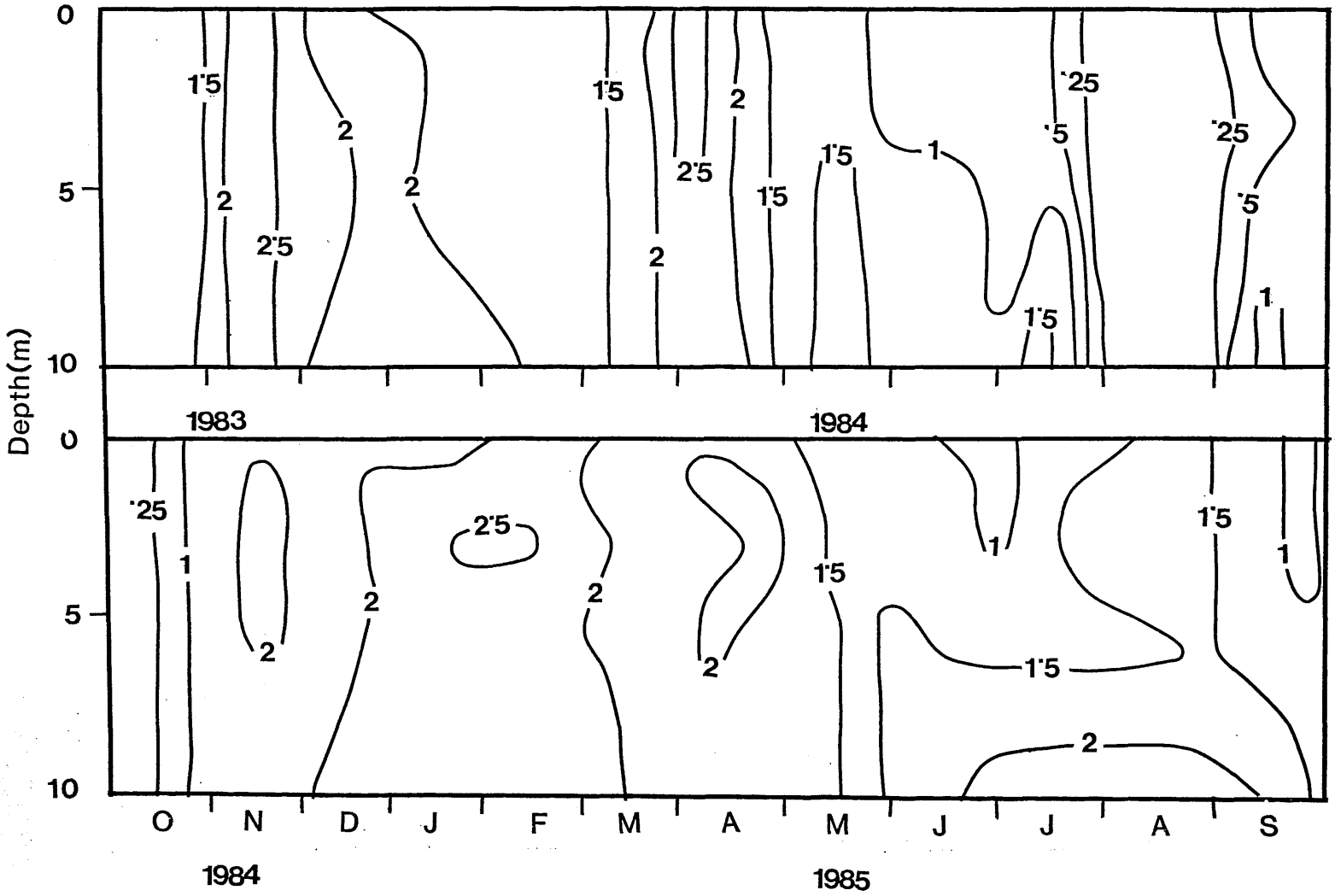
The slight increase of orthophosphate during autumn and winter (1985) could be related to repressed biological activity (Moss, 1973). The decline of orthophosphate throughout the water column in spring and in the epilimnion in the summer (1984) could be related with increased biological activity. Orthophosphate increase in the epilimnion during the summer (1985) coincides with the maximum inflow. During thermal stratification, the rapid increase of orthophosphate in the hypolimnion was observed only in 1985. The factors involved in such increase are not fully understood. However, it is widely accepted (Mortimer, 1941 - 42 ; Hutchinson, 1957 and Reid, 1961) that this phosphorus is released from the flocculent layer of the sediment by the reduction of an insoluble ferric phosphorus complex to soluble ferrous form and the associated release of phosphorus occur when the oxidized micro-zone disappear from the sediment surface. In 1984, hypolimnetic oxygen declined to 5% saturation (Fig. 5) and in 1985 hypolimnion was completely deoxygenated. The rapid increase of orthophosphate during the totally anoxic condition of the latter year seems to be reasonable.

3.3.2.7. Silicate :

Silicate concentrations showed distinct seasonal and vertical distribution patterns similar to the orthophosphate

Figure 19. Seasonal variations of silicate at station 1 from October, 1983 to September, 1985. Isopleths of silicate are expressed in mg/l.

Silicate - Station 1



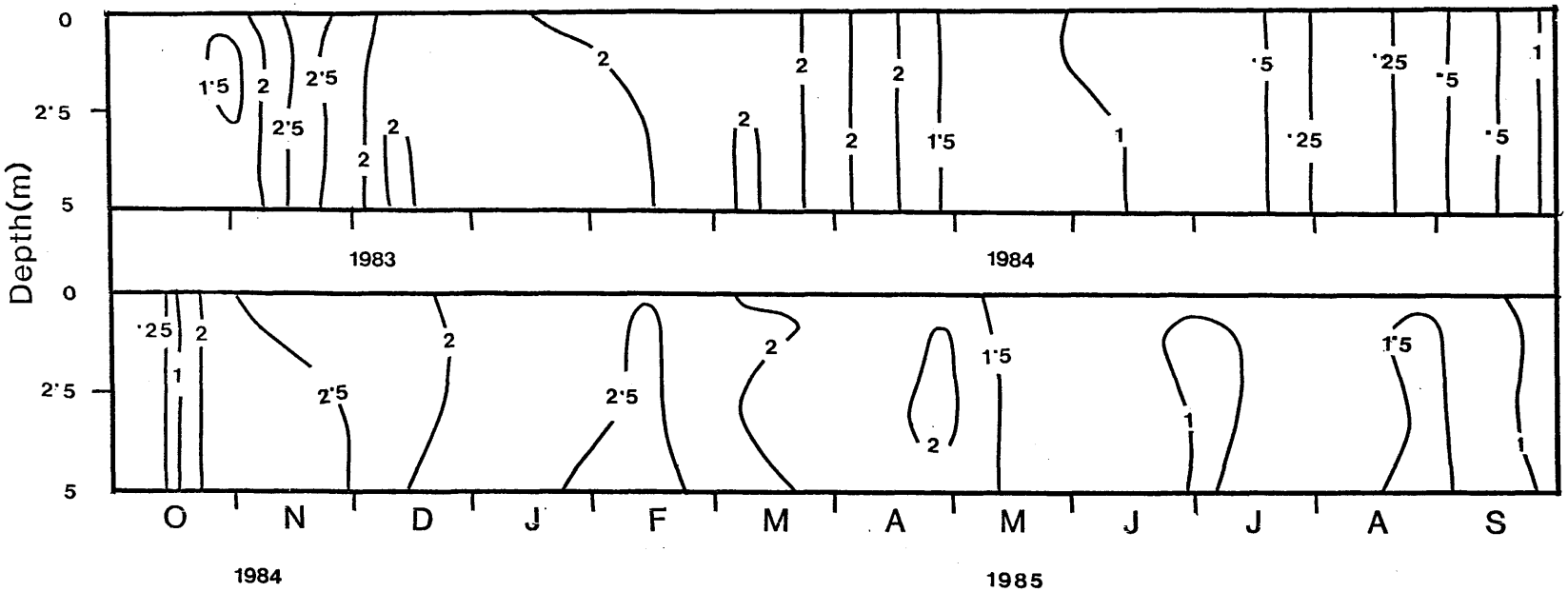
concentrations. It varied from less than 0.25mg/l to 2.5mg/l.

In deep water at station 1 (Fig. 19), silicate concentrations increased sharply from 1.5mg/l in October, 1983 to 2.5mg/l in November. From December, the concentrations declined sharply through the winter and reached to 1.5mg/l in early April, 1984. From late April, the concentrations gradually declined to less than 0.25mg/l during late July to early September throughout the water column. Slight vertical stratification was observed from June to mid July and in mid September. After autumn overturn, the concentrations started to increase from 0.25mg/l in mid October and reached to 2mg/l in November and December.

In 1985, silicate concentration was at the highest level (2.5mg/l) in January and February and then declined slightly through the spring and reached to 1.5mg/l in mid May throughout the water column. During thermal stratification, silicate concentrations in the epilimnion declined slightly from June to mid July and again in September to minimum level but the extreme depletion experienced in the previous year did not occur. In the hypolimnion, the concentrations increased slightly (2mg/l) from late June to early September with decreasing oxygen

Figure 20. Seasonal variations of silicate at station 2 from October, 1983 to September, 1985. Isopleths of silicate are expressed in mg/l.

Silicate - Station 2



saturation.

In shallow water at station 2 (Fig. 20), silicate concentrations did not show vertical stratification and the seasonal patterns were similar to the surface waters at station 1.

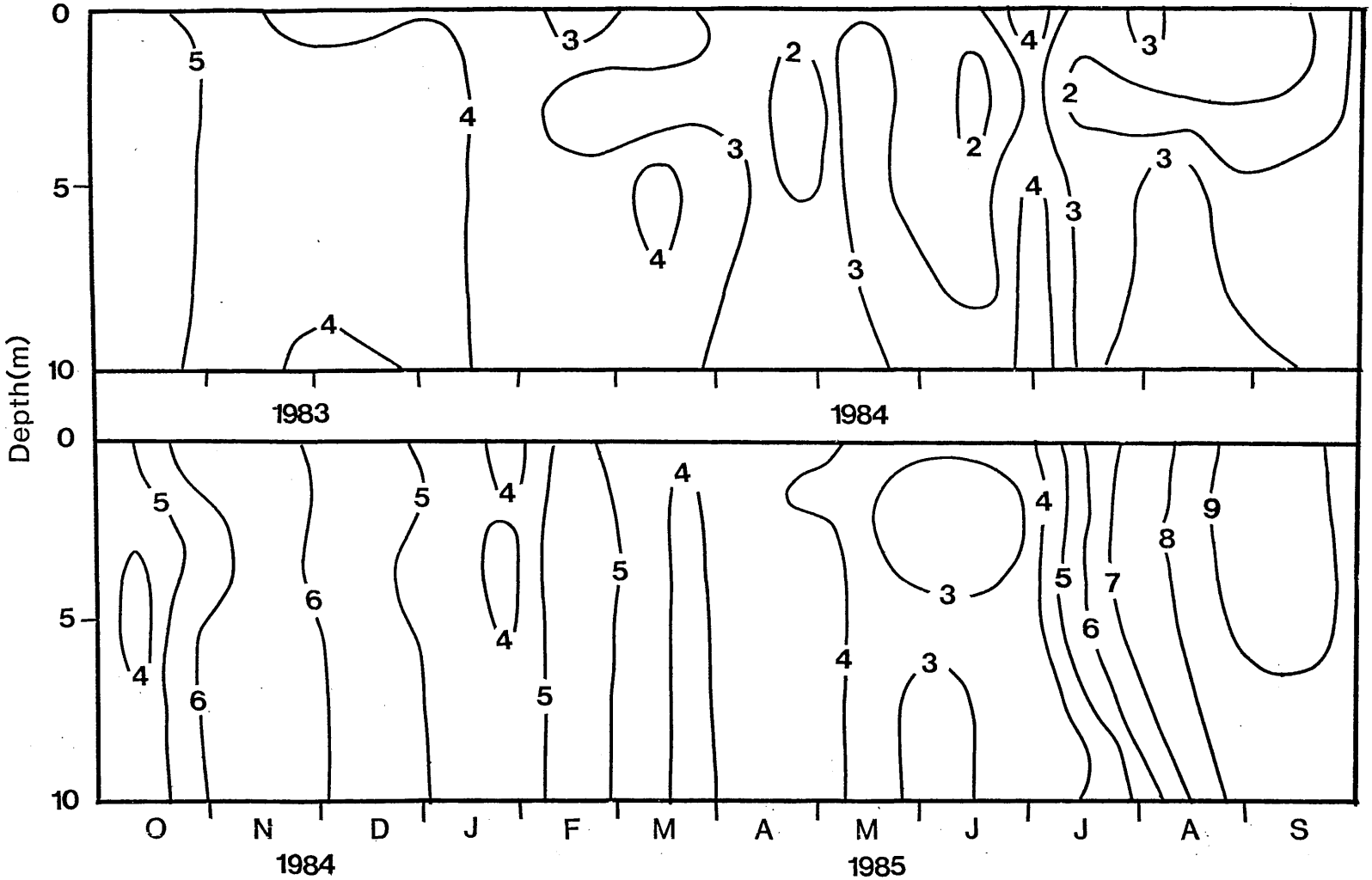
Klarer (1978) observed seasonal patterns of silicate in Dubh Lochan similar to 1985 but his values were lower (maximum concentrations 1.25mg/l) than in the present study.

The major sources of silica in natural waters is from the decomposition of aluminosilicate minerals in the drainage basin from which the water flows (Hutchinson,1957). The silicate content of the lake as a whole, is evidently largely controlled by the inflow of water (Yoshimura, 1930). In Dubh Lochan, the periods of high concentrations of silicate from late autumn to mid spring throughout the water column were associated with high rainfall (Table 1) which is also reflected by the water level measurements (Fig. 2).

Most workers reported that diatom blooms constitutes the most important mechanism by which silica is removed from the lake waters. The slight reduction of silicate in the early spring in 1984 and late spring in 1985 could be related to diatom production. Silicate depletion in the

Figure 21. Seasonal variations of dissolved organic carbon at station 1 from October, 1983 to September, 1985. Isopleths of dissolved organic carbon are expressed in mg C/l.

Dissolved organic carbon - Station 1



epilimnion during the early summer of 1984 and the lowest level throughout the water column in late July to early September corresponds to a bloom of an algal species Dinobryon divergens which incorporates small amounts of silica in its lorica and produce siliceous resting spores. Diatom and other algae that utilized silica were a very minor component of the phytoplankton in Dubh Lochan. It is probable that littoral algal communities, particularly epiphytes and some other macrophytes e.g. Equisetum sp., were responsible. Comparatively higher concentrations of silicate in the epilimnion during the summer of 1985 than the previous year is associated with greater inflow of water in such a wet year. Hypolimnetic increase of silicate during summer stagnation was probably due to the mineralization of diatom frustules and Dinobryon spores sedimented since the previous stratification rather than the release of chemically bound silicate from the sediment (Golterman, 1975).

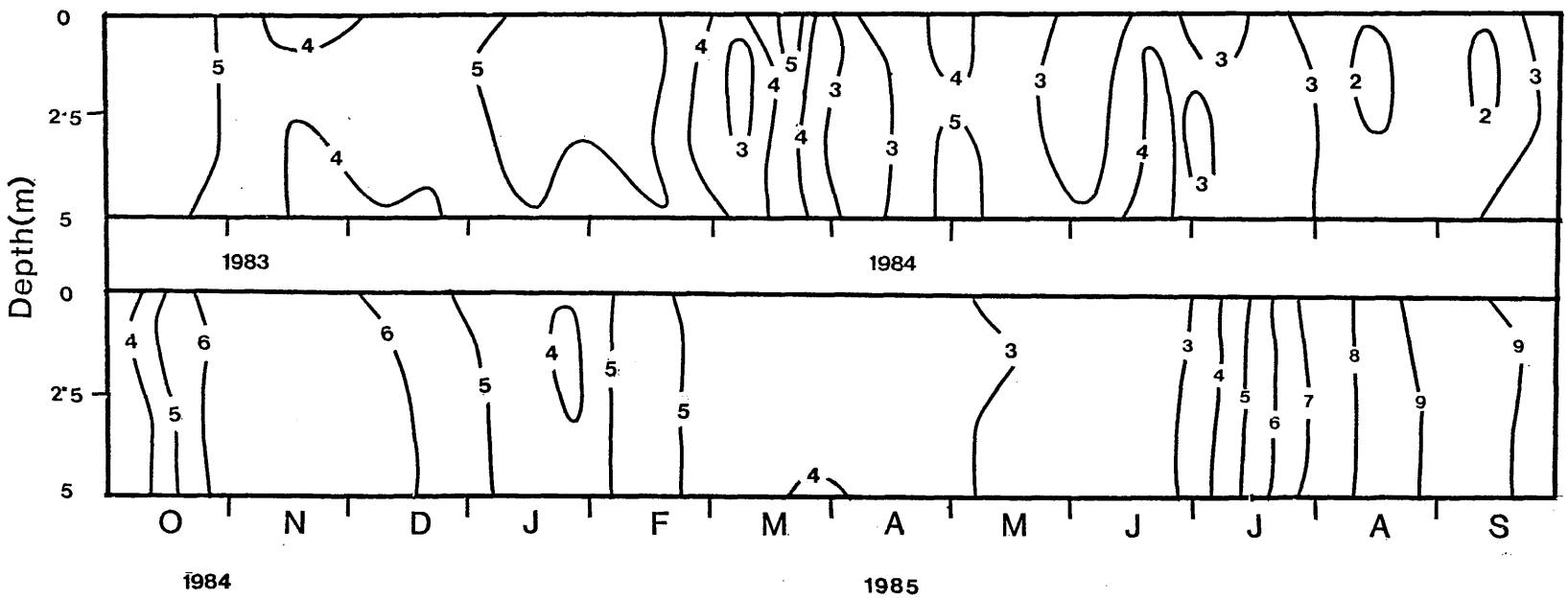
3.3.2.8. Dissolved organic carbon :

Dissolved organic carbon concentrations showed distinct seasonal distribution patterns and the values ranged from 1.9mg/l to 9.4mg/l.

In deep water at station 1 (Fig. 21), the

Figure 22. Seasonal variations of dissolved organic carbon at station 2 from October, 1983 to September, 1985. Isopleths of dissolved organic carbon are expressed in mg C/l.

Dissolved organic carbon - Station 2



concentrations declined gradually from 5mg/l in October, 1983 to about 3mg/l in March, 1984. From April onward the concentration remained very low ranging from 1.9mg/l to 4mg/l. During spring and summer, the concentrations were slightly lower in the upper waters than the bottom waters. After the autumn overturn, dissolved carbon concentrations increased rapidly and reached to about 6mg/l in late October to early December.

In 1985, the concentrations were higher than 1984. They declined gradually from 5mg/l in February to 3mg/l during mid May and mid June. From early July, the concentrations increased rapidly from 3mg/l to 9.4mg/l in September.

In shallow water at station 2 (Fig. 22), no vertical stratification of dissolved carbon was observed and the seasonal patterns were similar to station 1.

Dissolved organic carbon in lake water is derived from both autochthonous and allochthonous sources. Almost certainly high inflow - rapid runoff includes much of humic substances from peat layers up on the moorlands in the upper reaches of the catchment. The highest concentrations of organic carbon in the summer of 1985 could be related with the maximum inflow of water carrying allochthonous organic matter from the surrounding area. High

concentrations during autumn and winter could be related with declining phytoplankton populations in autumn and low population in winter at a time of high inflow in to the lake. Although the water colour was not measured during the present study, it was noticed that during the periods of high carbon concentrations the water colour became brown. The declining carbon concentrations throughout the spring coincides with spring phytoplankton bloom and the lowest concentrations in the summer of 1984 is associated with the maximum phytoplankton production at a time when the allochthonous input was minimal. Slightly lower concentrations in the upper waters during spring and summer of 1984 could be related with the uptake of organic carbon by phytoplankton. During thermal stratification and hypolimnetic anoxia, no noticeable vertical variation of dissolved organic carbon was observed. Birge & Juday (1934) reported that the great changes of dissolved oxygen content in the hypolimnion have little effect on the total dissolved organic carbon in the lake.

3.3.3. Biological :

During the spring and early summer, the littoral zone of Dubh Lochan develops dense beds of both submerged and emergent vegetation. As the littoral vegetation and the littoral benthos play important roles in both nutrient and

Table 3. Species composition of aquatic vegetation in Dubh Lochan.

Bryophyta :

Calliergon cuspidatum (Hedw.) Kindb.

*Fontinalis antipyretica Hedw.

Racomitrium aciculare (Hedw.) Brid.

*Sphagnum cuspidatum Ehrh. ex. Hoffm. emend.

*S. recurvum P. Beauv (S. intermedium auct.)

*S. subsecundum Nees

Pteridophyta :

Monocotyledones :

Carex curta Good

C. demissa Hornem

C. echinata Murr.

C. panicea L.

C. rostrata Stokes

C. vesicaria L.

Eriophorum angustifolium Honck.

*Equisetum fluviatile L.

Juncus acutiflorus Hoffm.

J. bufonius L.

J. bulbosus L.

J. effusus L.

Narthecium ossifragum (L.) Huds.

Phalaris arundinacea L.

*Phragmites australis (Cav.) Trin. ex Stued.

*Potamogeton natans L.

*P. polygonifolius Pourr.

Dicotyledones :

Callitriche stagnalis Scop.

Chrysosplenium oppositifolium L.

Elatine hexandra (Lapierre) DC.

Galium uliginosum L.

Hippuris vulgaris L.

Littorella uniflora (L.) Aschers.

*Lobelia dortmanna L.

Menyanthes trifoliata L.

*Myriophyllum alterniflorum DC.

*Nuphar lutea (L.) Sm.

*Nymphaea alba L.

Polygonum hydropiper L.

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* Common

Table 4. Species composition of zoobenthos in Dubh Lochan.

Ephemeroptera :

*Leptophlebia marginata L.

*L. vespertina L.

Plecoptera :

*Nemoura cinerea Retzius.

*Perla bipunctata (Pictet) Klap.

Odonata :

*Cordulegaster boltonii Don.

Cordulia aenea L.

Enallagma cyathigerum Charp.

Ischnura elegans Vander Linden.

Pyrrhosoma nymphula Sulzer

Megaloptera :

*Sialis lutaria L.

Trichoptera :

Beraeidae

Cyrnus flavidus McLachlan

*Holocentropes marmoratus Curtis

*Limnephilus sp.

Phryganeidae

Polycentropus sp.

Hemiptera :

*Calicorixa praeusta Fieb

Corixa punctata Illig.

*Notonecta glauca L.

*Sigara distincta Fieb

S. falleni Fieb

S. fossarum Leach

S. scotti D. & S.

Coleoptera :

*Agabus congener Thun.

Copelatus agilis Fab.

*Dysticus marginalis L.

Gyridae

Diptera :

*Chaoborus flavicans Meigen.

*Chironomus plumosus L.

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* Common.

plankton dynamics of freshwater ecosystems, a general biological survey of the flora and fauna was conducted. The species composition of aquatic vegetation is presented in Table 3 and the zoobenthos in Table 4. The most commonly occuring species are marked with asterisks.

The following 4 species of fish are present in Dubh Lochan, Esox lucius L., Gasterosteus aculeatus L., Anguilla anguilla L., and Perca fluviatilis L.(Klarer, 1978).

The members of zooplankton community are dominated by Copepods, Cladocerans and Rotifers (see chapter 5).

Zooplankton and some members of zoobenthos are the main consumers of phytoplankton. The fish, Chironomid larvae and some other Dipteran larvae are the major predators of zooplankton.

CHAPTER — 4.

PHYTOPLANKTON AND PRIMARY PRODUCTION

4.1 Introduction :

Phytoplankton play a very important role in the production process in aquatic ecosystems particularly lentic ones. It converts solar energy into chemical energy by the process of photosynthesis. This energy is the major source of food to the consumers in the ecosystem. Phytoplankton is also important in detritus formation (Moss, 1982) which in turn is an important source of food for a wide range of detritivore organisms. The production of organisms in the secondary and tertiary levels of the two main pathways of energy flow is therefore, directly related with the production of phytoplankton. Successful growth of phytoplankton may cause nutrient depletion in the environment and after their death and decomposition nutrients may be returned to the system. The death and decomposition of green and blue-green algae may under certain circumstances cause a serious problem by releasing toxic substances particularly after bloom formation. Proper knowledge of phytoplankton is therefore, essential in understanding the energy transfer process in aquatic ecosystems.

4.2. Materials & Methods :

4.2.1. Phytoplankton :

Water samples for phytoplankton enumeration were collected between January, 1984 and December, 1985 every fortnight at station 1 from surface, 1m, 3m, 5m and 10m depths. On returning to the laboratory, the samples were poured immediately in to 1 litre measuring cylinders and preserved with 10ml Lugol's iodine solution. After about 24 hours, when the plankton was well sedimented, the supernatant was siphoned very carefully down to about 10ml with fine Teflon tubes. The samples were then made up to 25ml with distilled water, transferred to 25ml capacity counting chambers and sedimented again for at least 24 hours. Phytoplankton were counted with an inverted microscope at 200x magnification using micro-transect technique (Margalef, 1969). To determine the number of transects required for a representation, 10 micro-transects were counted across the counting chamber and the accumulated number of species were plotted against the number of transects. It was found that 3 transects were enough to represent more than 90% of the species. Counts of 3 transects were, therefore, used in routine phytoplankton enumeration. During the period of exponential growth of

certain species, which mostly occurred between April and August, it was often impossible to count even one complete transect under 200x magnification.

For such species, the individuals in 5 microscope fields were counted separately at 400x magnification. The number of fields required to count for a representative sub-sample was determined following the same technique described above. The micro - transect method was followed for the enumeration of the rest of the species in the same sample. Counts were multiplied by a factor to convert the results to numbers of individuals per litre.

The phytoplankton were identified according to Barber & Haworth (1981); Bourrelly (1968, 1970, 1972); Cleve-Euler (1951-1955); Lind & Brook (1980); Pascher (1930); Prescott (1962, 1964); Ward & Whipple (1959) and West & West (1904-1923). The phytoplankton identifications were normally checked by Dr. R. Tippett.

4.2.2. Primary production :

Primary production rates were determined every fortnight between January, 1984 and December, 1985 using Carbon ^{14} tracer technique (Vollenweider, 1969). Water samples were collected at station 1 from surface, 1m, 3m, 5m

and 10m depths. The samples were poured in 125ml capacity light and dark bottles. Duplicate sets of light and dark bottles were always used for each depth. 0.5ml radioactive solution containing approximately 0.5 µci Carbon ^{14} ($NaH C^{14} O3$) was injected into each bottle using a Finnpipette (200-1000µl). The duplicate sets of light and dark bottles were incubated *in situ* for exactly 4 hours. Dark bottles were used to compensate for any dark uptake of Carbon ^{14} (Strickland & Pearsons, 1972). After the incubation period, the samples were carried to the laboratory in a light proof wooden box to prevent further carbon fixation. To trap the labelled algae, 50ml sub-samples from each bottle was taken for filtration to minimise cell breakage during vacuum filtration as suggested by Arthur & Rigler (1967). The sub-samples were filtered through HA (0.45µm) millipore membrane filters using a vacuum pump. The filter papers containing the samples were placed in labelled vials and dissolved in 15ml Unisolve 1 liquid scintillation fluid. The specific activity of the fixed Carbon ^{14} in the samples were determined using an internal standard method on a liquid scintillation counter. Vials for original activity and for background were also counted. Great care was always taken during the collection, incubation and filtration of the samples to the light. The processing was also done as quickly as possible and never took longer than 3 hours. From readings at the 5 depths, a production profile for the water

*An analysis of variance could be calculated, however, Romo (1987), (M.Sc. Thesis, Univ. Glasgow) conducted similar experiment in lake Rusky during the same period using same facilities, technique and equipment and reported 48% error in the whole method. A similar level of error is also expected in the present study.

column was obtained, the values integrated and results are expressed in terms of energy fixed per square metre lake surface per month.

Carbon ^{12} available for photosynthesis was calculated from alkalinity and pH values at the appropriate depth (Mackereth, 1963). The calculations were made with a computer using a programme developed by Mr. T. Bladon.

The disadvantage of Carbon ^{14} method is that it can not differentiate net and gross photosynthesis. During respiration phytoplankton produce carbon dioxide and some of this respiratory carbon dioxide is internally recycled for use in photosynthesis during the progress of the experiment. The method therefore, measures a quantity somewhere between net and gross photosynthesis and the problem is that this point is not fixed. The real advantage of the method is its sensitivity. The method is particularly suitable in such habitats as Dubh Lochan where phtoplankton populations are very sparse especially during winter months. *see opposite.

4.3. Results and Discussion :

4.3.1. Species composition :

A total of 158 species and varieties of phytoplankton

Table 5. Species composition and abundance of phytoplankton in Dubh Lochan.

Number	Abundance	Species
		Phylum : Chlorophyta
		Class : Chlorophyceae
1	+	Ankistrodesmus falcatus (Corda) Ralfs.
2	+	Arthrodesmus bifidus Breb. var. latidivergens.
3	+	A. incus (Breb.) Hass. var. minor
4	+	A. triangularis Lagerh. var. subtriangularis
5	+	Bambusina brebissoni Kutz.
6	C	Botryococcus braunii Kutz.
7	+	Chlamydomonas dinobryonii G. M. Smith
8	+	C. globosa Snow
9	R	Chlorella ellipsoidea Gerneck
10	+	*Cladophora fracta var. lacustris (Kutz.) Brand
11	+	Closterium didymotocum Corda

12	+	C. gracile Breb.
13	+	C. striolatum Ehr.
14	R	C. toxon West
15	+	*Coleochaete irregularis Pringsheim
16	+	*C. orbicularis Pringsheim
17	+	Cosmarium amoenum Breb.
18	+	C. contractum (Elfv.) West & West var. ellipsoideum
19	+	C. crenatum Ralfs.
20	+	C. dentiferum Corda
21	+	C. margaritiferum Menegh.
22	+	C. subtumidum Nordst.
23	+	C. tintum Ralfs.
24	+	Cosmocladium saxonicum DeBary
25	+	*Crucigenia quadrata Morren.
26	+	C. tetrapedia (Kirch) West & West
27	+	*Dactylococcus infusionum Naegeli
28	+	Dictyosphaerium pulchellum Wood
29	+	Euastrum bidentatum Nag.
30	+	E. crassum (Breb.) Kutz.
31	+	E. denticulatum (Kirchn.) Gay
32	+	E. pulchellum Breb.
33	+	Gloeocystis planctonica (West & West) Lemmerman
34	+	G. vesiculosa Nag.
35	+	Micrasterias truncata (Corda) Breb.

36	+	Microspora pachyderma (Wille) Lagerheim
37	+	M. Willeana Lagerheim
38	+	Mougeotia sp.
39	+	Netrium digitus (Ehr.) Itzigs & Rothe
40	+	N. oblongum (DeBary) Lutkem var. cylindicum
41	+	*Oedogonium sp.
42	C	Oocystis lacustris Chod.
43	C	O. rhomboides Fott.
44	C	O. solitaria Wittr.
45	+	Pediastrum boryanum (Turp.) Meneghini
46	+	Penium cruciferum (DeBary) Wittr.
47	+	P. margaritaceum (Ehr.) Breb.
48	+	Pleurotaenium coronatum (Breb.) Rabenh.
49	+	P. nodosum (Bail.) Lund
50	+	Protoderma viride Kutz.
51	+	*Rhizoclonium heiroglyphicum (C.A.Ag.) Kutz.
52	+	Scenedesmus denticulatus Lagerheim
53	+	S. quadricauda (Turp.) Breb.
54	+	*Selenestrum minutum (Naeg.) Collins
55	C	Sphaerocystis schroeteri Chod.
56	+	Staurastrum brevispinum (Breb.) West & West var. obversum
57	+	S. gracile Ralfs.
58	+	S. inconspicuum Nordst.
59	+	S. paradoxum Meyen.

60	+	*Stigeoclonium nanum Kutz.
61	+	*Tetraedron duospinum Ackley
62	+	T. minimum (A. Braun) Hansgirg
63	+	Tetrallantos lagerheimii Teiling
64	+	Ulothrix aequalis Kutz.
65	+	U. moniliformis Kutz.
66	+	U. subconstricta West
67	+	Xanthidium antilopaeum (Breb.) Kutz.
68	+	X. armatum (Breb.) Rabenh.
69	+	Zygnema sp.

Phylum : Euglenophyta

70	+	Trachelomonas oblonga Lammermann
71	+	T. volvocina Ehr.

Phylum : Chrysophyta

Class : Chrysophyceae

72	+	Dinobryon divergens Imhof
73	+	Mallomonas acaroides Perty
74	+	M. producta (Zacharias) Iwanoff

75	+	Achnanthes lanceolata (Breb.) Grun.
76	+	*Amphora ovalis Kutz.
77	+	Anomoeonis serians (Breb.) Cleve
78	+	*Caloneis bacillum Grun.
79	+	*Ceratoneis arcus Kutz.
80	+	*Cocconeis placentula Ehr.
81	+	Cyclotella operculata (Ag.) Kutz.
82	+	Cymbella aequalis W. Smith
83	+	C. bipartita Mayor
84	+	C. gracilis (Rabh.) Cl.
85	+	*C. prostrata (Berkeley) Cleve
86	+	C. ventricosa Kutz.
87	+	Diatoma vulgare Bory
88	+	Eunotia arcus Ehr.
89	+	E. curvata (Kutz.) Lagest.
90	+	E. exgracilis (W. Smith) A. Cl.
91	+	*E. faba (Ehr.) Grun.
92	+	*E. lunaris (Ehr.) Grun.
93	+	E. minutisima A. Cl.
94	C	E. pectinalis (Kutz.) Rabh. var. minor (Kutz.) Rabh.
95	+	E. pectinalis (Kutz.) Rabh. var. undulata Ralfs. Rabh.
96	+	*E. paludosa Grun.

97	+	*E. serra* Ehr.
98	+	*E. tenella* (Grun.) A. Cl.
99	F	*Frustulia rhomboides* (Ehr.) de Toni var. *Crassinervia* (Creb. ex W. Sm.) Ross
100	+	*F. rhomboides* (Ehr.) de Toni var. *saxonica* (Rabh.) de Toni
101	+	**Gomphonema acuminatum* Ehr.
102	+	**G. gracile* Ehr.
103	+	*G. lanceolatum* Ehr.
104	+	**G. olivaceum* Ehr.
105	+	*G. parvulum* (Kutz.) Grun.
106	+	*Hantzschia amphioxys* (Ehr.) Grun.
107	+	**Melosira italica* (Ehr.) Kutz.
108	R	*Navicula cryptocephala* Kutz.
109	R	**N. cuspidata* Kutz.
110	+	**N. exilissima* Grun.
111	R	**N. exigua* (Gregory) O. Muller
112	+	**N. lanceolata* (Ag.) Kutz.
113	+	**N. oblonga* Kutz.
114	R	*N. subtilissima* Cl.
115	+	*Neidium affine* (Ehr.) Cl.
116	+	**N. productum* (W. Smith) Cleve
117	+	**Nitzschia hantzschiana* Rabh.
118	+	*N. lanceolata* W. Smith
119	+	**N. sigmoidea* (Ehr.) W. Smith
120	C	*Peronia heribaudi* Brun & Per.

121	+	Pinnularia biceps Greg.var.gregorii A.Cl.
122	+	P. biceps Greg. var. typica A. Cl.
123	+	*P. gibba Ehr.
124	+	*P. interrupta W. Smith
125	+	P. stauroptera (Rabh.) Cl.
126	+	*Rhoicosphaenia curvata (Kutz.) Grun.
127	+	Stauroneis anceps Ehr.
128	+	Stenopterobia intermedia (Lewis) Fricke
129	+	*Surirella elegans Ehr.
130	+	*S. linearis W. Smith
131	+	*S. ovalis Breb.
132	+	Tabellaria fenestrata (Lyngh.) Kutz. var. intermedia Grun.
133	+	T. fenestrata (Lyngh.) Kutz. var. lacustris Meister
134	C	T. flocculosa (Roth.) Kutz.

Phylum : Pyrrhophyta

Class : Dinophyceae

135	+	Ceratium hirudinella (O.F.Muller) Schrank.

Class : Cryptophyceae

136	C	Cryptomonas marssoni Skuja
137	C	C. ovata Ehr.

138	+	Rhodomonas minuta Skuja

Phylum : Rhodophyta

Class : Rhodophyceae

139	+	*Batrachospermum boryanum Sirodt.
140	+	B. moniliforme Roth.

Phylum : Cyanophyta

Class : Myxophyceae

141	+	Aphanocapsa delicatissima West & West
142	+	A. pulchra (Kutz.) Rabh.
143	+	Aphanothece saxicola Nag.
144	+	Calothrix ephiphytica West & West
145	+	*Chroococcus turgidus (Kutz.) Naegeli
146	R	Coelosphaerium naegelianum Unger.
147	+	Cylindrosphermum minutum Wood
148	+	Gomphosphaeria lacustris Chord.
149	+	Lyngbya limnetica Lammermann
150	+	L. perelegans Lammermann
151	+	*Merismopedia elegans A. Braun.
152	+	M. glauca (Ehr.) Nag.
153	+	*Microcystis aeruginosa (Kutz.) Elenkin
154	+	Nostoc paludosum Kutz.
155	+	*Oscillatoria minima Gicklhorn

156	+	O. subbrevis Schmidle
157	+	O. tenuis C. A. Ag.
158	+	*Spirulina major Kutz.

A represents abundant : Occur in more than 90% of the samples and often represents more than 25% of the community.

C represents common : Occur in between 33% and 66% of the samples, sometimes represents more than 10% of the community.

F represents faithful : Occur in more than 66% of the samples but never represent more than 1% of the community.

R represents rare : Occur in between 33% and 66% of the samples but never represents more than 1% of the community.

+ represents present : Occur in less than 33% of the samples and never represent more than 1% of the community.

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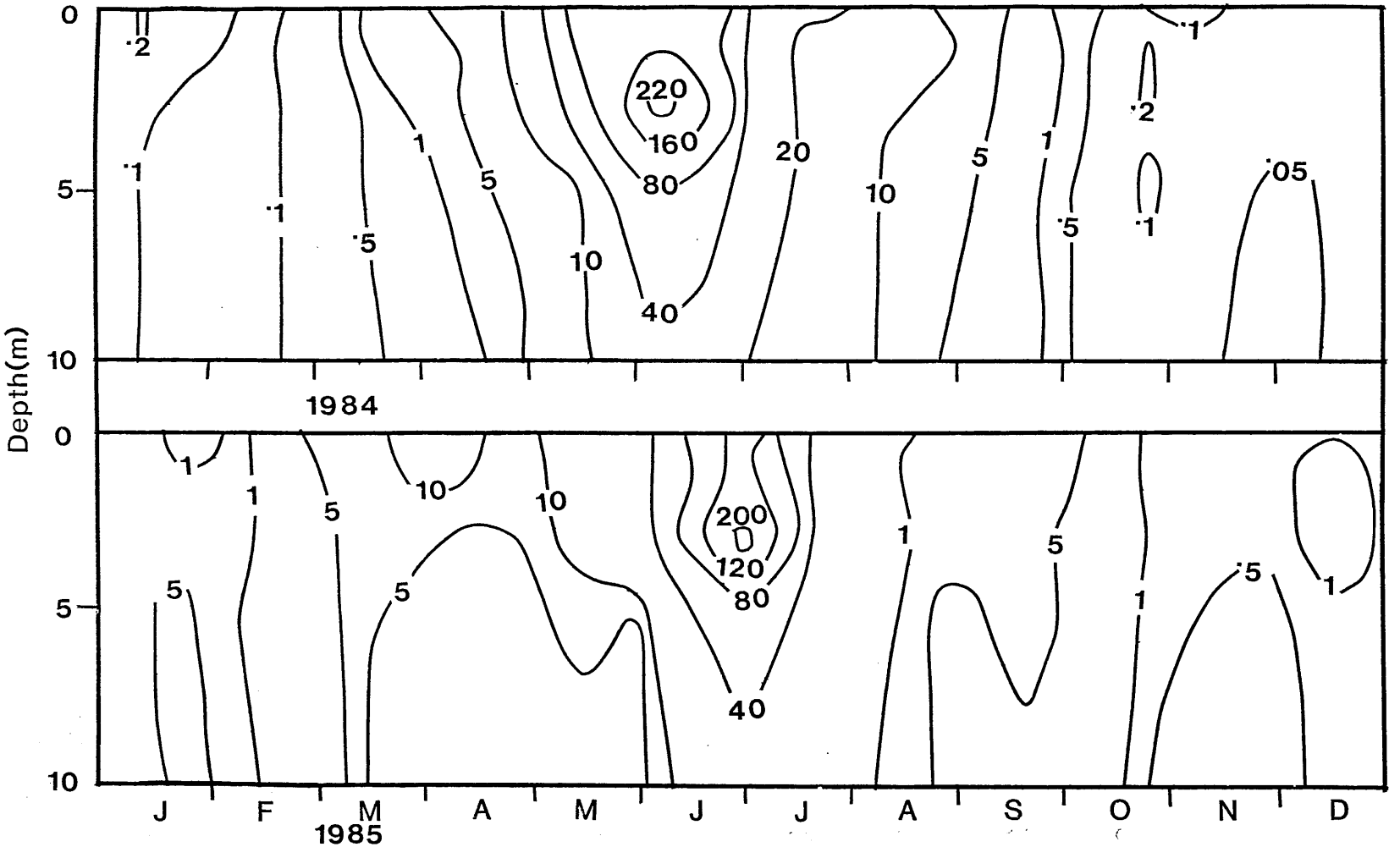
were identified during the period of study. A list of the species along with a simple indication of their abundance are presented in Table 5. Although many species of desmids and diatoms were identified, neither of the group was an important component of phtyoplankton in Dubh Lochan. All the desmids and most of the diatoms appear to have been littoral in origin, they were probably washed into the plankton by wind induced turbulance. Klarer (1978) reported 147 species of algae in Dubh Lochan. The present study adds 12 species of Chlorophyta, 27 species of Chrysophyta, 1 species of Rhodophyta and 5 species of Cyanophyta to the existing species list of phytoplankton in Dubh Lochan. The newly recorded species have been asterisk marked (Table 5). On the contrary 19 species of Chlorophyta, 2 species of Chrysophyta, 4 species of Pyrrhophyta and 2 species of Cyanophyta which were recorded earlier were not observed during the present study. The non overlappimg species were all taxonomically quite distinct and can not be accounted for by error in identification.

4.3.2. Phytoplankton biomass (expressed as number/l) and commmunity pattern :

Phytoplankton biomass showed distinct seasonal and strong vertical distribution patterns (Fig. 23). A single early summer maximum was apparent in both the years.

Figure 23. Seasonal variations of phytoplankton biomass from January, 1984 to December, 1985. Isopleths of phytoplankton biomass are expressed as number x 10^5/l.

Phytoplankton biomass



In 1984, phytoplankton biomass was very low from January to March. From late April, it increased gradually and reached to its peak in mid June and then declined sharply in late June. From early July, the biomass declined gradually through the rest of the year with lowest numbers during Novemeber and December. During the peak, the highest biomass was observed between 2 and 5m depth. However, from April to early September, it was always higher in the epilimnion than the rest of the water column.

In 1985, the seasonal pattern of phytoplankton biomass was similar to the year before. Phytoplankton biomass during spring was approximately 5 times higher than 1984. The peak in summer occurred three weeks later and the biomass was slightly smaller than the previous year. During the summer peaks in both the years the biomass was greatly influenced by the rapid growth of Sphaerocystis schroeteri (Fig. 24).

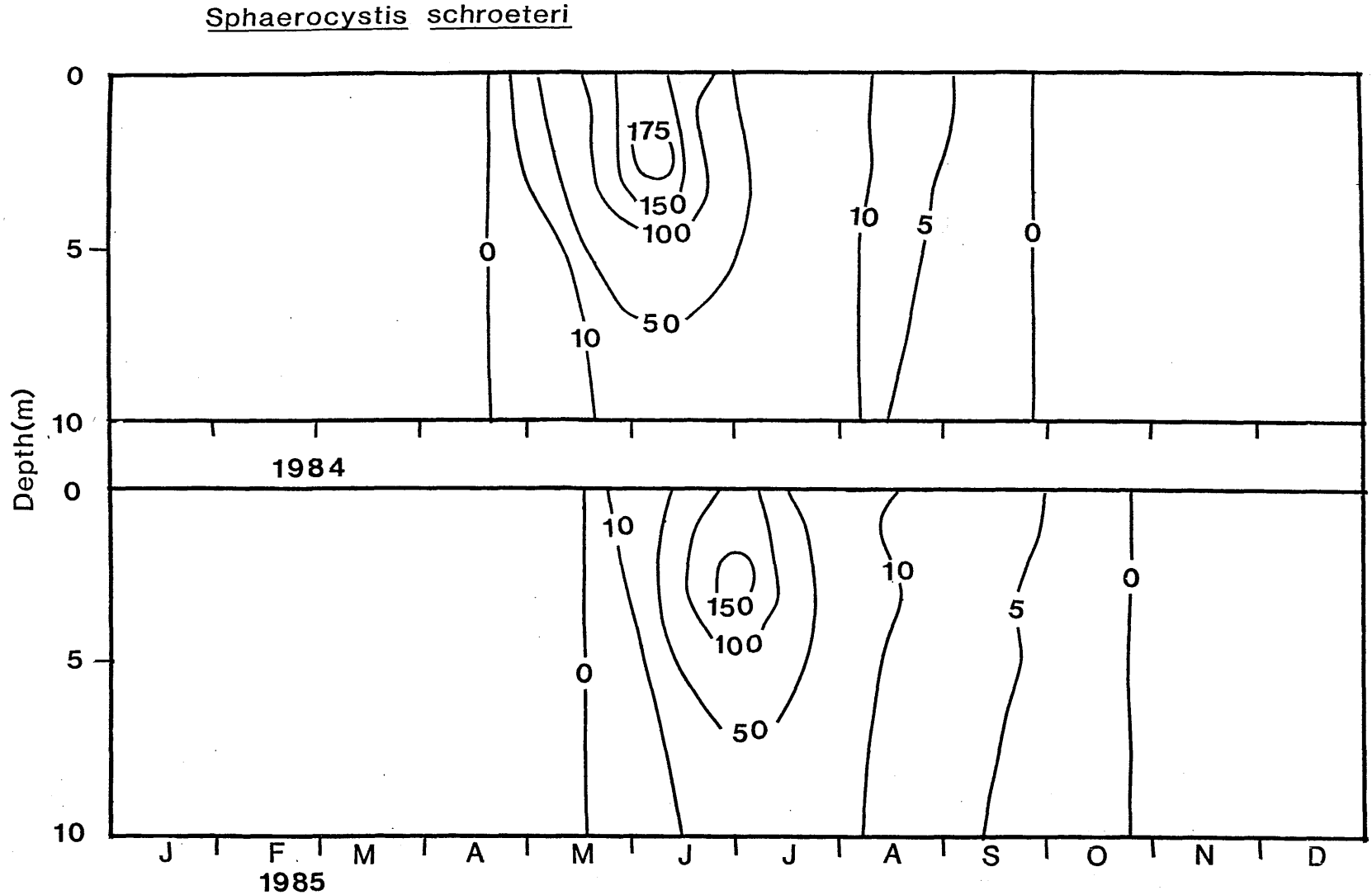
Klarer (1978) reported a single summer peak of phytoplankton biomass in 1974 and 1976 and two peaks, one in spring and the other in summer in 1975 in Dubh Lochan. Hutchinson (1967) discussed seasonal patterns of total phytoplankton from different types of waterbodies and suggested that in oligotrophic water a single summer peak is

common. However, spring and autumn maxima have also been reported but during such maxima, phtoplankton is generally dominated by diatoms.

Before attempting the seasonal patterns of individual species, a general community pattern of phtoplankton in Dubh Lochan is described.

In January and February, the diatoms especially Peronia herebaudi and Eunotia pectinalis were dominant in the phytoplankton. Green flagellates dominated during late March and early April and then the populations declined in May. From late April to May (1985), Dinobryon divergens and Cryptomonas spp., reached their peaks but D. divergens was the dominant species. Phytoplankton biomass increased rapidly in June and July because of rapid growth of Sphaerocystis schroeteri. During this time D. divergens (1984), Cryptomonas spp., Oocystis spp., and Botryococcus braunii also reached to their peaks but S. schroeteri was the dominant species. After the summer peak, phytoplankton biomass declined sharply in August and a gradual decline throughout the autumn lead to its minimum in December. During this decline B. braunii was the dominant species in August, green flagellates again assumed dominance in September and diatoms again dominated in November and December, although phytoplankton biomass was very low.

Figure 24. Seasonal variations of Sphaerocystis schroeteri from January, 1984 to December, 1985. Isopleths are expressed as number x 10^5/l.


Sphaerocystis schroeteri
Depth(m)
0
5
10
175
150
100
50
10
0
10
5
0
1984
0
5
10
10
150
100
50
0
10
5
0
J
F
M
A
M
J
J
A
S
O
N
D
1985

Klarer (1978) also reported similar community patterns of phytoplankton in Dubh Lochan. Green flagellates dominated in spring and autumn, D. diergens in early summer, S. schroeteri in mid summer and Oocystis spp., in late summer. However, the diatoms were never reported to be present in significant numbers but in the present study they seem to be more important than Klarer's (1978).

4.3.3. Individual species pattern :

Although 158 different algal species and varieties were identified during the present study, 11 species were recorded frequently enough to permit an examination of individual seasonal succession and vertical distribution patterns.

4.3.3.1. Sphaerocystis schroeteri :

Sphaerocystis schroeteri was the dominant species during summer. It showed distinct seasonal and vertical distribution patterns (Fig. 24) with a single summer peak in both the years.

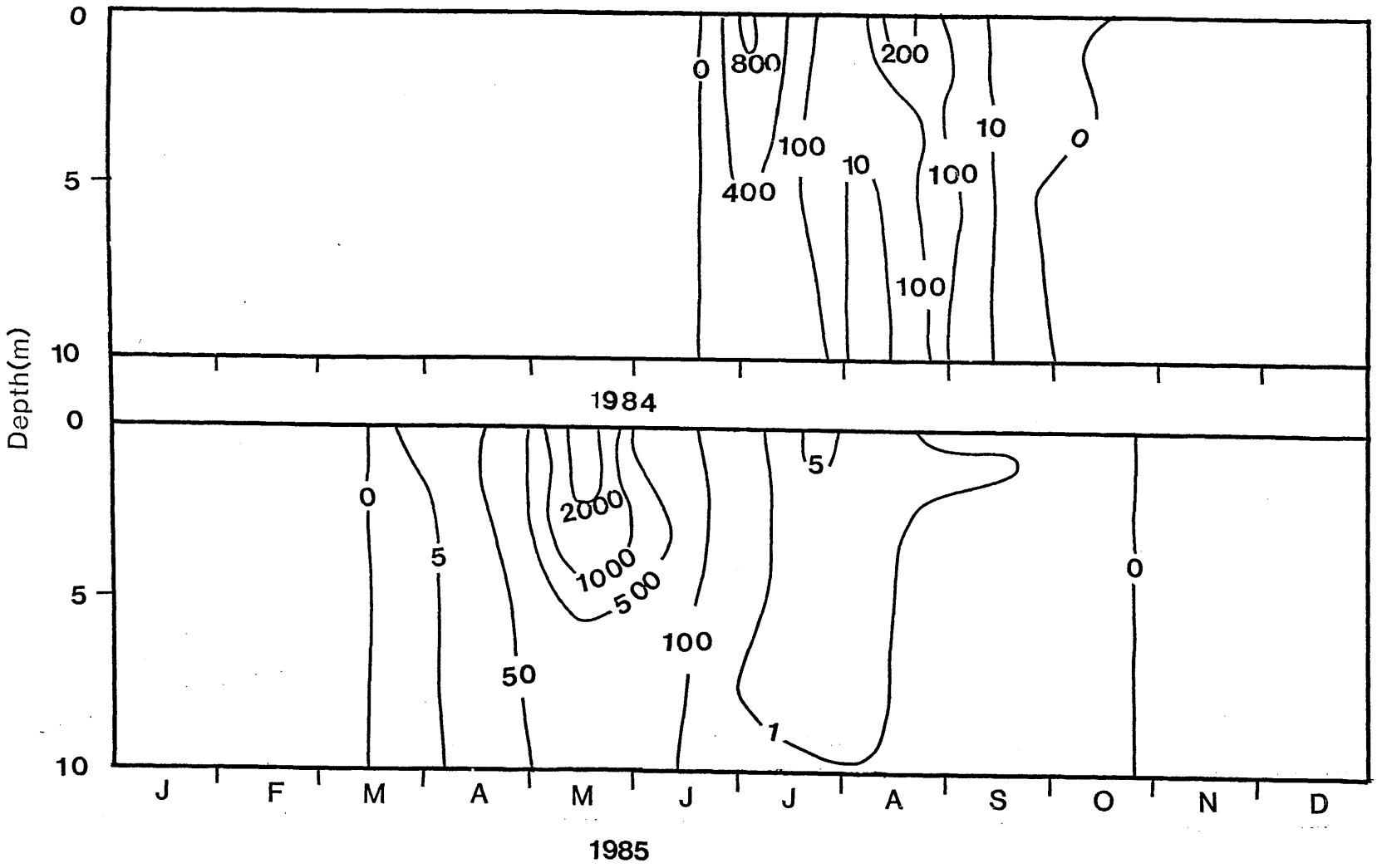
In 1984, the species first appeared in late April and a rapid increase in May resulted its maximum in early June

when the lake was thermally stratified and the surface water temperature was about 18°C. The species showed strong vertical stratification with highest populations in the epilimnion. After the peak, the populations declined rapidly in June. From July it declined gradually and disappeared in late September.

The seasonal pattern in 1985 was similar to the year before. The species first appeared in late May. The peak occurred a month later than its counterpart in 1984. The peak population was slightly smaller than the year before and the maximum number of colonies were again observed in the epilimnion. Both the increase and decrease of the populations before and after the peak was very rapid. The population level during August and September were similar to the previous year and the species disappeared by late October. During the peak in 1984, nitrate concentrations (Figs. 13 & 14) were moderately high but orthophosphate concentrations (Figs. 17 & 18) were very low. In 1985, nitrate concentrations were low but orthophosphate concentrations were slightly higher than 1984.

Hutchinson (1967) reported that Sphaerocystis sp., may develop very high populations and could be very important in unproductive lakes. Klarer (1978) reported that the species was dominant during the summer months but was observed

Figure 25. Seasonal variations of Dinobryon divergens from January, 1984 to December, 1985. Isopleths are expressed as number x 1000/l.


Dinobryon divergens
Depth(m)
0
5
10
0
800
200
100
400
10
100
10
100
0
1984
0
5
10
0
2000
5
1000
500
100
50
1
0
J
F
M
A
M
J
J
A
S
O
N
D
1985

through the entire year. He observed two peaks of S. schroeteri, the major peak was in mid summer and a minor peak in late summer in 1974 and 1975 and a single peak in late summer in 1976. Pearsall (1932) observed highest populations of S. schroeteri in autumn and was common in spring in the English Lake District. Davies (1972) reported a mid summer peak of the species in Hogans pond in Newfoundland.

4.3.3.2. Dinobryon divergens :

Dinobryon divergens was one of the dominant species in Dubh Lochan. The seasonal succession of the species showed considerable differences between the two years (Fig. 25).

In 1984, it first appeared in mid June and a sudden peak of large population numbers occurred in late June to early July when the lake was thermally stratified and the surface water temperature was 19°C (Figs. 3 & 4).

It declined sharply in late July and again increased to a second and smaller peak in late August when the surface water temperature was at its highest level (20°C). The populations declined sharply in September and disappeared by late October. The first peak was about 4 times larger than the second peak. The growth and decline of these peak

populations were always very rapid. During both the peaks, the largest populations were observed at the surface and they declined sharply with increasing depth.

In 1985, D. divergens showed a single peak. It first appeared in March and then a gradual increase lead to its maximum in mid May when thermal stratification started to develop and the surface water temperature was 11°C. The population size during this peak was about 2.5 times larger than the early summer peak in 1984. The largest population during this period was also observed in the epilimnion and declined sharply with increasing depth. From late June to late September, the populations were very low and was no longer observed by late October.

Klarer (1978) observed a single early summer maximum in 1974 and two maxima, one in early summer and the other in late summer in 1975 and 1976.

Dinobryon divergens is considered to be a cool water species with optimum population between 8.5°C and 13.2°C (Hutchinson, 1967; Lehman, 1976a). Findenegg (1943b) observed highest population when the water temperature was 5°C. In the present study, water temperature ranged between 11°C and 13°C during the period of Dinobryon succesession. It is evident that D. divergens succession could occur in a

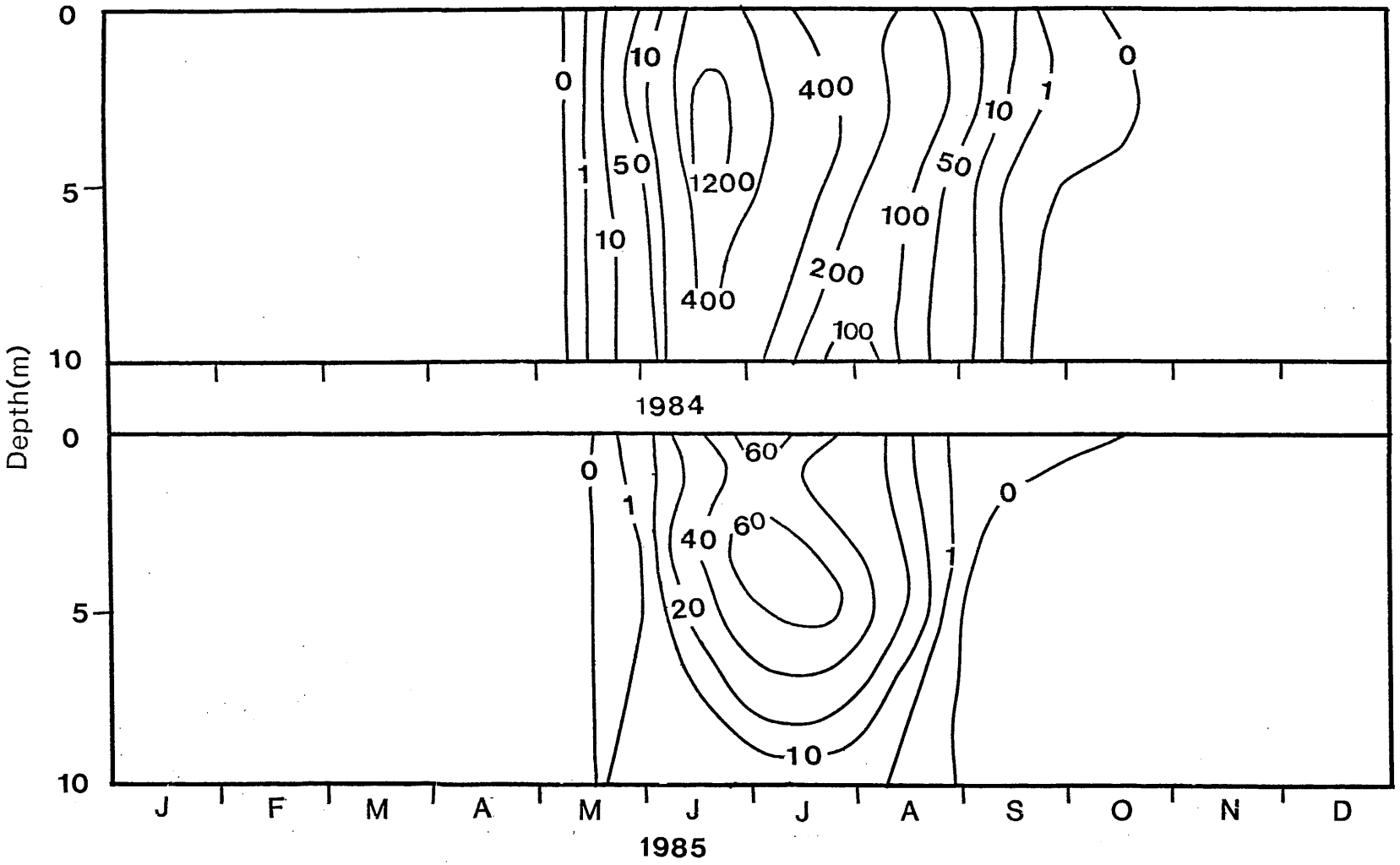
wide range of temperature. Dinobryon spp., are characteristic of nutrient depletion, particularly orthophosphate deficient waters (Hutchinson, 1967). The available information suggest that the members of this genus are able to grow in waters with orthophosphate levels below some critical level between 1 & 5 µg/l (Hutchinson, 1967) although different races in different lakes may have slightly different requirements (Rodhe, 1948). In Dubh Lochan, the succession of Dinobryon divergens occurred when orthophosphate levels were 0.1 µg/l in 1984 and was below detectable level in 1985. Findenegg (1943b) considered D. divergens to be a spring species but Hutchinson (1967) suggested that nutrient levels in water were more important in determining the seasonal succession of the species.

4.3.3.3. Oocystis spp. :

Three species of Oocystis, O. lacustris, O. rhomboidea and O. solitaria were recorded during the period of study. They were bulked together because of difficulty in separating the species while counting under inverted microscope due to very high numbers in peak period. However, O. lacustris was dominant among the three species in both the years. Oocystis spp., were present in Dubh Lochan from May to October and showed a single summer

Figure 26. Seasonal variations of Oocystis spp., from January, 1984 to December, 1985. Isopleths are expressed as number x 1000/1.

Oocystis spp.



maximum in both the years (Fig. 26).

In 1984, Oocystis spp., first appeared in mid May coinciding with the development of thermal stratification. The populations increased rapidly from late May and reached to its peak in late June when the lake was thermally stratified and the surface water temperature was 19°C. It declined gradually from July through August and September and disappeared by late October when the thermal stratification broke down resulting complete overturn. The population levels were generally high in July and August. Strong vertical stratification was observed during the peak with highest population levels between 2 and 5m depth. During the rest of the period, the populations in the epilimnion were slightly higher than the rest of the water column.

In 1985, the seasonal patterns were similar to the year before but the population levels were comparatively lower during the whole period. The peak occurred in late June to late July and was approximately 20 times smaller than the year before. Both the increase and decrease of the populations were gradual. Strong vertical stratification was observed from mid June to mid August with highest population number in the epilimnion and very low numbers in the hypolimnion.

Nitrate concentrations (Figs. 13 & 14) during both the peaks were low. Orthophosphate concentrations (Figs. 17 & 18) were also low but it was slightly higher in 1985 than 1984 although the populations did not show an increase with the increased concentrations of orthophosphate. During isothermal periods when the nutrient concentrations were high, Oocystis spp., was absent in the lake.

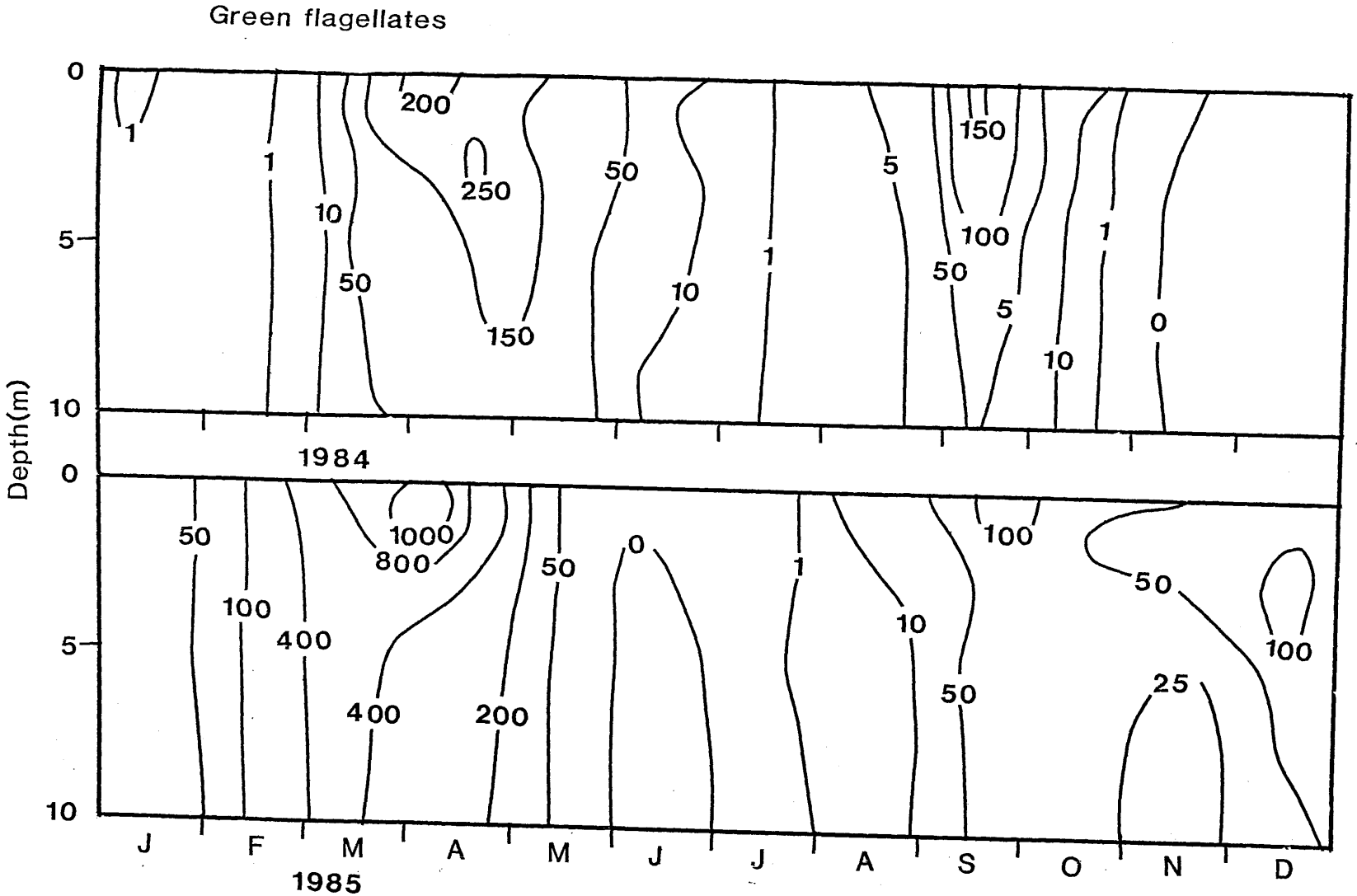
Klarer (1978) reorted two separate peaks of Oocystis spp., in Dubh Lochan, a major peak in late spring to early summer and a minor peak in late summer and the populations were confined to the epilimnion and metalimnion.

Hutchinson (1967) reported that Oocystis spp., are characteristics of oligotrophic water and occur mainly in summer. They are capable of developing immense population when the inorganic nutrients are at a very low level.

4.3.3.4. Green flagellates:

Two types of green flagellates were recognized and distinguished as flagellate 1 and flagellate 2 according to the usage of Klarer (1978). Flagellate 1 is oovoid in shape, unicellular with two flagella. Flagellate 2 is depressed globose to broadly ovoid with strongly flattened

Figure 27. Seasonal variations of green flagellates from January, 1984 to December, 1985. Isopleths are expressed as number x 1000/l.


Green flagellates
Depth(m)
0
5
10
1984
1985
J
F
M
A
M
J
J
A
S
O
N
D
1
10
50
200
250
150
1
50
10
1
5
150
100
50
5
1
10
0
50
100
400
1000
800
400
200
50
0
1
10
50
100
50
100
25

anterior surface, unicellular with a single flagellum. Their size varied from 3 to 7 microns in diameter. (see Klarer, 1978 for more detailed description of the two forms). However, the flagella could not be seen easily and were not visible at all while counting under inverted microscope. For this reason in the present study they were bulked under the general grouping as green flagellates.

Green flagellates were common during the whole period of study. They showed two distinct seasonal peaks (Fig. 27), one in spring and the other in autumn in both the years. The populations were generally higher in 1985 than in the previous year.

In 1984, the populations were very low in winter, then a gradual increase lead to its spring maximum in March and April at a time when both nitrate (Figs 13 & 14) and orthophosphate (Figs. 17 & 18) concentrations were high. With the onset of thermal stratification and declining nutrient concentrations, the populations declined gradually and reached its minimum level in July. The populations started to increase again from late August and reached a second maximum in mid September at the same time as thermal stratification was begining to break down and the nutrient concentrations were still low. After the autumn overturn population numbers declined to low level in October and low

level remained until December. The spring peak was as big as the autumn peak.

In 1985, the seasonal patterns were similar but the spring peak was approximately 10 times bigger than the autumn peak. The population level in January and February were high coinciding with high concentrations of orthophosphate. The spring peak was approximately 4 times bigger than in 1984 and the autumn peak was slightly smaller.

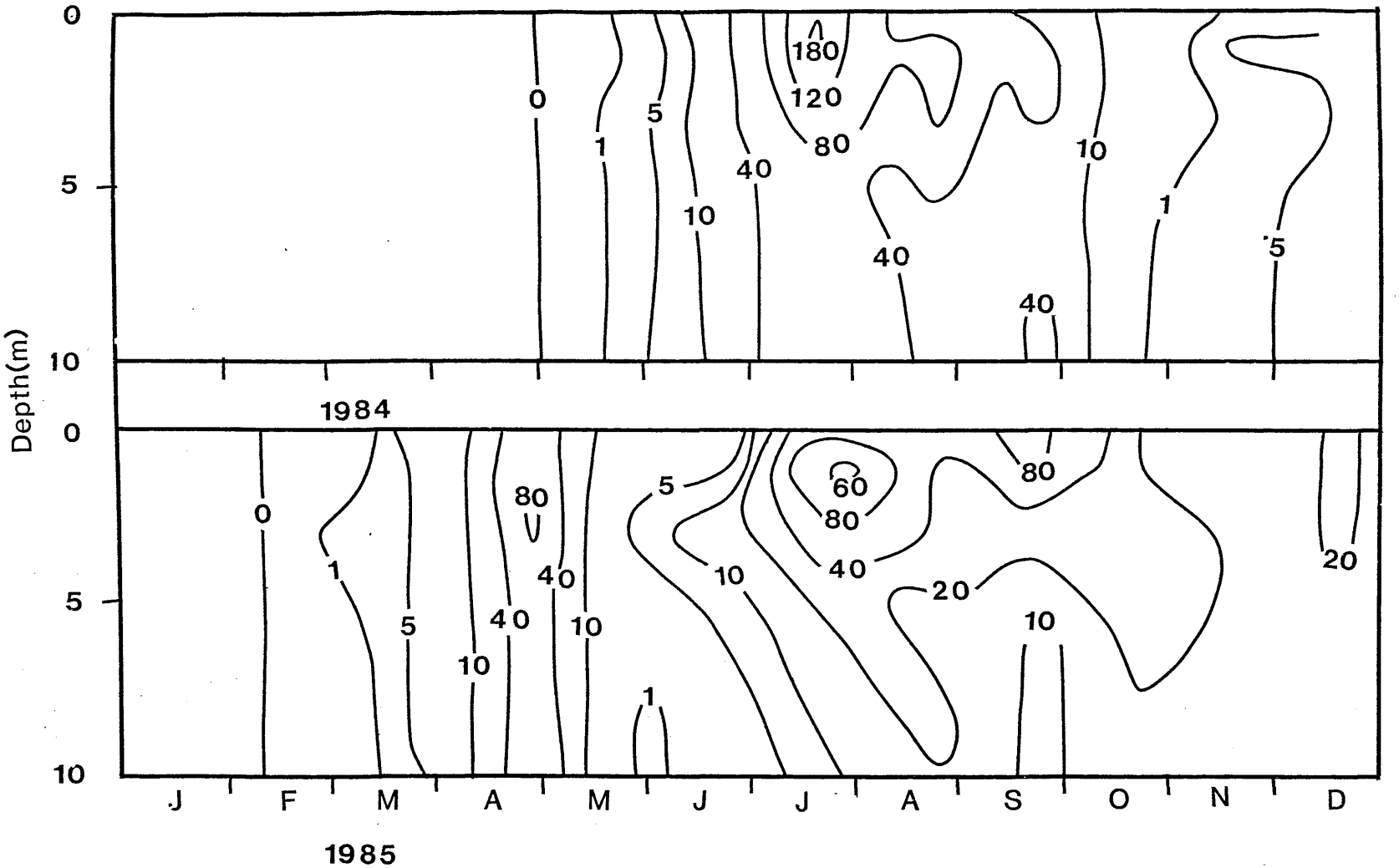
Population numbers from May to August were much lower but from October to December their numbers were much higher than the year before.

Strong vertical stratification was observed during the peaks in both the years with maximum numbers in the top 4m water and they were homogeneously distributed through the water column during the rest of the period.

Klarer (1978) reported that green flagellates were very low in 1974 with no distinct seasonal peak, moderate number in 1975 with a single spring peak and high population in 1976 with three separate peaks in winter, spring and summer and the populations were very low in autumn.

Figure 28. Seasonal variations of Cryptomonas spp., from January, 1984 to December, 1985. Isopleths are expressed as number x 1000/l.

Cryptomonas spp.



In the present study low summer population and high autumn population in 1985 is in contrast to Klarer's (1978) finding. However, the evidence suggests that the flagellates have wide range of temperature tolerance and need high nutient concentrations in the water for their optimum growth.

4.3.3.5. Cryptomonas spp. :

Two species of Cryptomonas, C. ovata and C. marsonii were recorded in the present study. They are bulked together under Cryptomonas spp. However C. ovata was in general the dominant species. Cryptomonas spp., were observed throughout the year except in January and February in 1985. Considerable differences was observed in the seasonal and vertical distribution patterns between the two years (Fig. 28). It showed a single summer peak in 1984 and three distinct peaks in spring, summer and autumn in 1985.

In 1984, the populations were very low from January to early March. A gradual increase from late March resulted its maximum in late July. It declined gradually from August and reached to its lowest level in December.

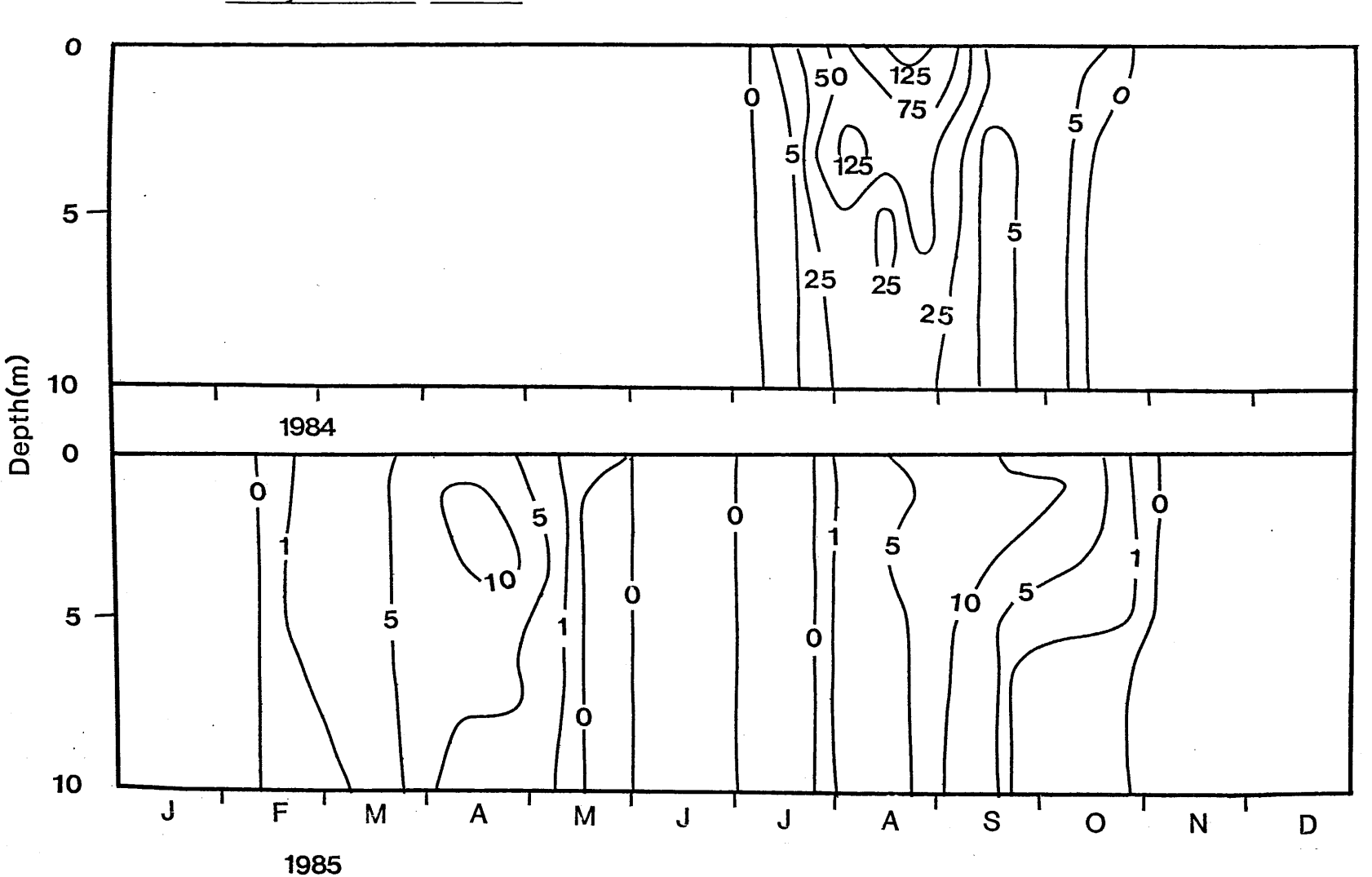
In 1985, Cryptomonas spp., was absent from January to mid February. It showed three distinct seasonal peaks, one

in late April to early May, one in late July to early August and a third one in late September to early October. The spring and autumn maxima were similar in size but the summer one was about 2 times larger than the others. The population levels in spring and autumn in 1985 were higher than the previous year. The summer maximum in 1984 was slightly larger than 1985. At the time of summer maximum, the peak populations were observed between surface and 4m depth. During the whole period of thermal stratification, the populations were always high in the epilimnion and it declined with increasing depth. The population was evenly distributed throughout the water column during isothermal condition.

Klarer (1978) observed two distinct seasonal peaks of Cryptomonas spp., in spring and autumn in 1974 and 1975 and a minor mid summer peak in 1976 in Dubh Lochan. He did not find any vertical stratification and the species was absent in June and July in 1974 and 1975. In the present study the highest peak was in mid summer and two other minor peaks in spring and autumn occurred only in 1985. Strong vertical stratification was observed during the whole period of thermal stratification.

During late summer in August and early September when the hypolimnion was anoxic, Klarer (1978) did not find

Figure 29. Seasonal variations of Botryococcus braunii from January, 1984 to December, 1985. Isopleths are expressed as number x 100/l.


Botryococcus braunii
Depth(m)
0
5
10
0
5
10
1984
1985
J
F
M
A
M
J
J
A
S
O
N
D

Cryptomonas spp., in the bottom waters but in the present study considerable numbers of the populations were also present in the anoxic waters in the hypolimnion.

Ilmavirta & Kotimaa (1974) reported from olagotrophic waters in Finland that Cryptomonas spp., were most common throughout the winter and in early summer but not in autumn. In the present study, the winter population was very low. The evidence suggests that Cryptomonas spp., have a wide range of temperature tolerance and capable of flourishing in very low nutrient concentrations but they need Vitamin B12 or Thiamin (Hutchinson, 1967) for their optimum growth.

4.3.3.6. Botryococcus braunii :

Botryococcus braunii was not a dominant component of phytoplankton in Dubh Lochan. The populations varied greatly between the two years (Fig. 29).

In 1984, B. braunii appeared in early July and then a rapid increase resulted in a maximum in late July to August when the lake was thermally stratified and the nutrient concentrations were low. The populations declined sharply in September and disappeared by late October. Strong vertical stratification was observed during the peak with highest populations in the upper 5m water.

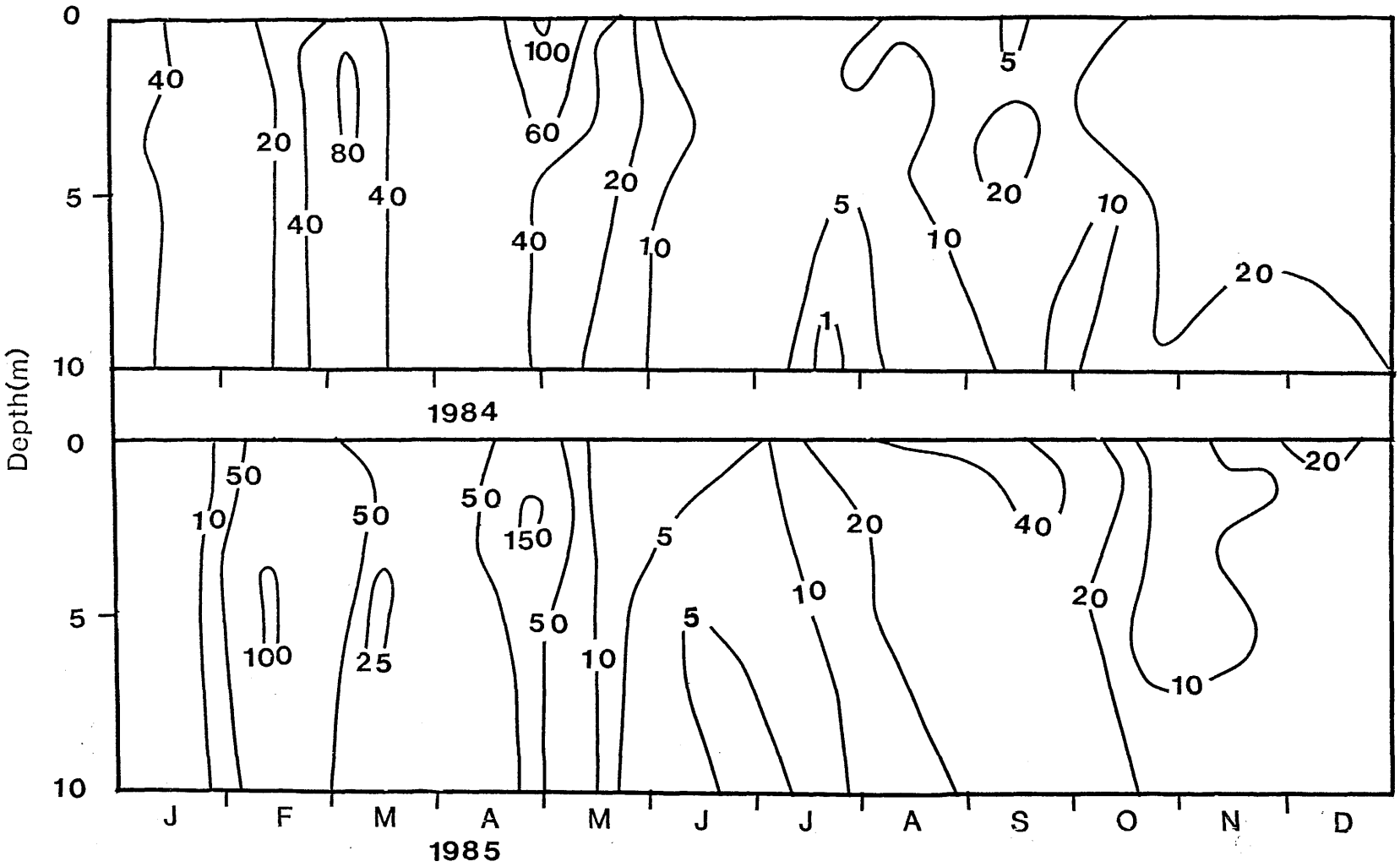
In 1985, B. braunii showed no distinct seasonal peaks and the populations were much lower than the previous year. However, the species appeared in mid February, increased slightly in March and April and then disappeared by mid May. The species was absent from mid May to mid July. It appeared again in late July, increased slightly in late August and September and again disappeared by late October. The rise of the population levels during spring and late summer were similar.

Klarer (1978) recorded B. braunii in Dubh Lochan in small numbers and did not observe seasonal succession. Maulood & Boney (1980) reported that the species was present in Loch Lomond throughout the year and showed a single summer peak in July and August. Chu (1942) suggested that B. braunii is autoauxotrophic but requires fairly high concentrations of nutrients for optimum growth.

On the contrary the maximum populations of B. braunii in July & August in the present study in Dubh Lochan and in Maulood & Boney's (1980) study in Loch Lomond occurred when the nutrient concentrations were low. Hutchinson (1967) suggested that the species can be extremely abundant but under conditions that are so varied that nothing can be said about its ecological determination.

Figure 30. Seasonal variations of Peronia herebaudi from January, 1984 to December, 1985. Isopleths are expressed as number x 100/1.

Peronia herebaudi



4.3.3.7. Peronia herebaudi :

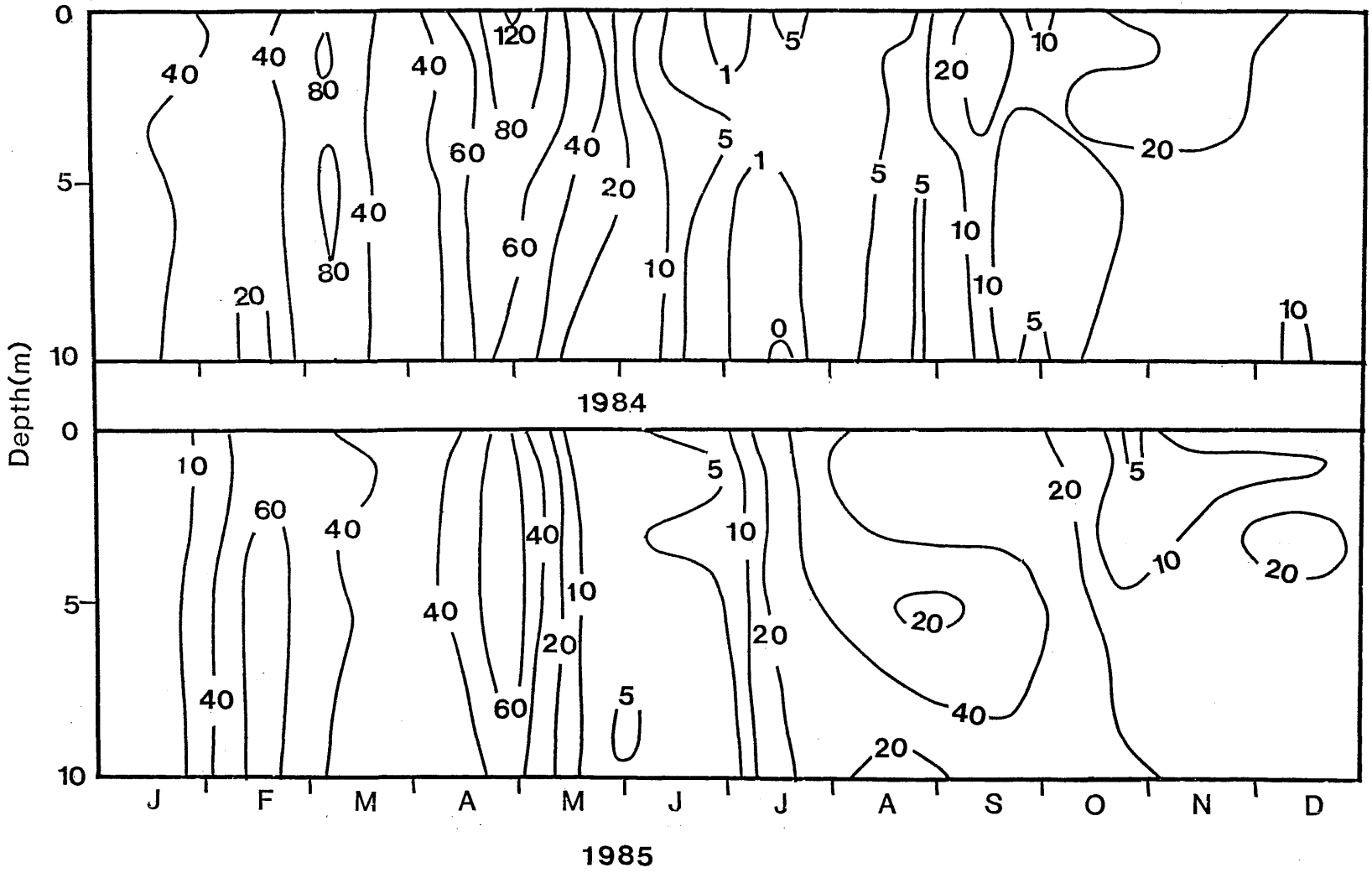
Peronia herebaudi was common among the diatom community in Dubh Lochan throughout the water column during the period of study. It showed distinct seasonal and slight vertical distribution patterns in both the years (Fig. 30).

In 1984, the population levels were high in January, decreased slightly in early February and then increased to its peak in late February to early March. It declined slightly in late March to early April and then increased again in late April to early May reaching its second peak. This peak was slightly bigger than the first peak. Slight vertical stratification was observed during both the peaks with highest population in the upper 4m water. With the onset of thermal stratification, the population level declined in late May and low numbers remained up to September. After the autumn overturn and redistribution of nutrients throughout the water column, the population increased slightly in October and remained up to December.

In 1985, the population levels in January were much lower than the year before. A sudden increase from late January lead to its first peak in mid February which is about 3 weeks earlier than the previous year. During this

Figure 31. Seasonal variations of Eunotia pectinalis from January, 1984 to December, 1985. Isopleths are expressed as number x 100/1.

Eunotia pectinalis



peak, the population levels were slightly higher than 1984 but the highest populations were observed between 4 and 6m depth. The spring peak was similar to 1984 but the highest population numbers were observed between 2 and 5m depth. From late May to July, the population levels were similar to the year before but it showed a minor peak in August and September in the epilimnetic water. From late October to December the populations were generally slightly lower than the year before.

4.3.3.8 Eunotia pectinalis :

Eunotia pectinalis was common in the planktonic diatom community in Dubh Lochan throughout the water column although it is benthic in origin (Hutchinson, 1967). It showed distinct seasonal distribution patterns (Fig. 31).

In 1984, the populations were generally higher than 1985. Starting from high numbers in January and February, it reached to its first peak in mid March. The populations declined slightly in late March to early April and then increased to its second peak in late April to early May when the nutrient concentrations especially nitrate and orthophosphate concentrations were high. This peak was slightly higher than the peak in March and the populations showed slight vertical stratification with maximum

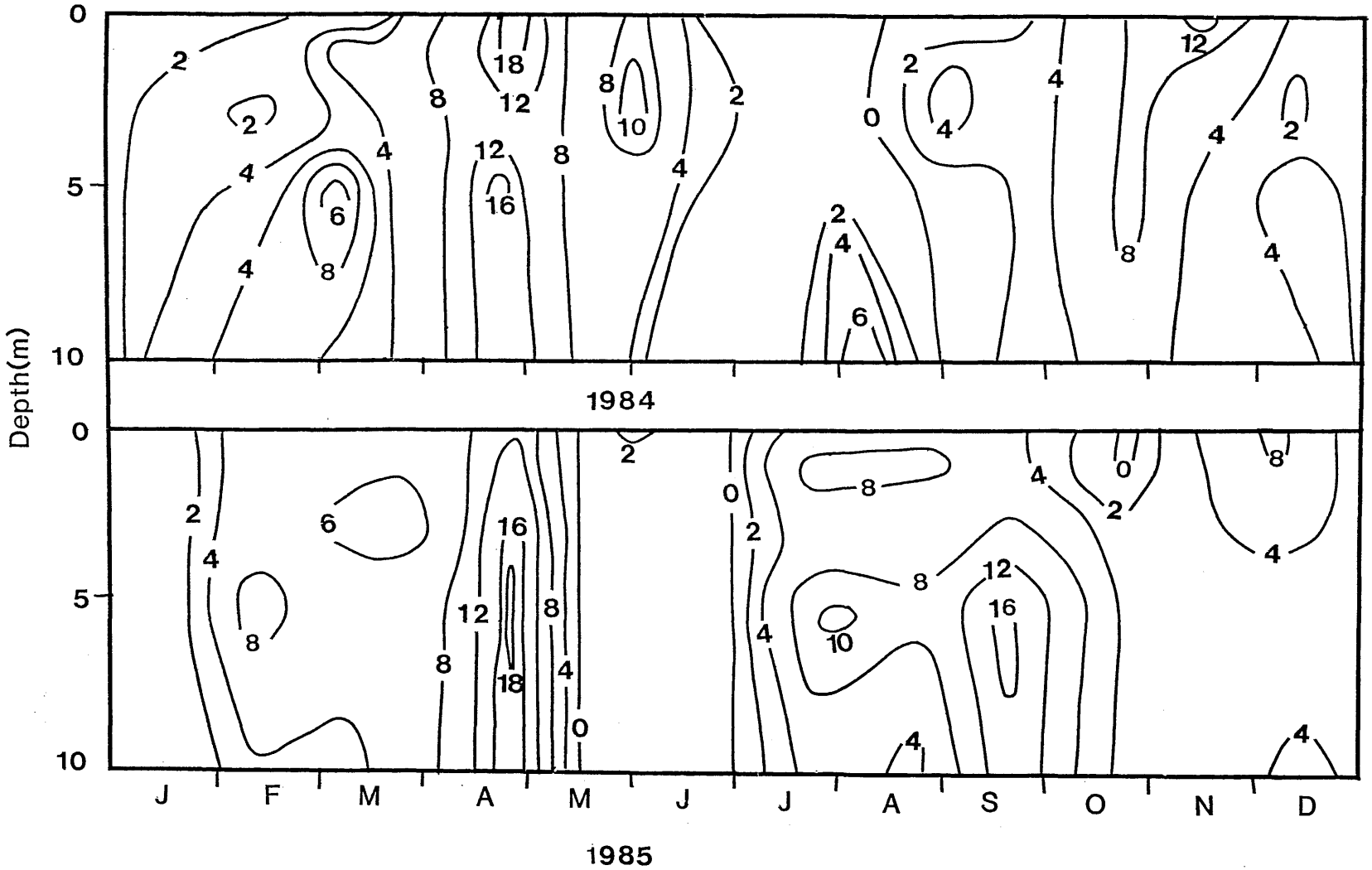
populations in the upper 4m water. With the onset of thermal stratification and declining nutrient concentrations, the populations declined gradually and reached to the lowest level in July and August. Although the populations increased slightly in September and October, the levels remained low throughout the autumn and early winter.

In 1985, the seasonal patterns were similar except in summer when the populations were higher than the year before. Eunotia pectinalis showed three small peaks, one in February, one in late April to early May and a third one in August and September. The winter and spring peak was similar in size but the summer peak was slightly small. The winter peak was slightly smaller than its counterpart in 1984 and the highest populations were observed between 3 and 10m depth. The spring peak was about half the size of 1984 peak and the populations were almost uniformly distributed throughout the water column. The population level during the whole summer were much higher than the year before. During the peak in August and September the highest populations were observed between 3 and 8m depth. The population level from October to December were similar to the year before but the numbers were slightly higher between 4 and 10m depth.

Klarer (1978) reported very low numbers of E. pectinalis in planktonic community but that it was common in

Figure 32. Seasonal variations of Eunotia lunaris from January, 1984 to December, 1985. Isopleths are expressed as number x 100/l.

Eunotia lunaris



the epiphytic communities in Dubh Lochan. However, wind induced turbulence and the increased buoyancy caused by bubbles of photosynthetically produced oxygen could probably be responsible for the mixing of this benthic diatom in to the plankton community in Dubh Lochan. In autumn, the 'substrate' for epiphytes particularly aquatic plants die back and become unstable, therefore, release many of the diatoms in to the water.

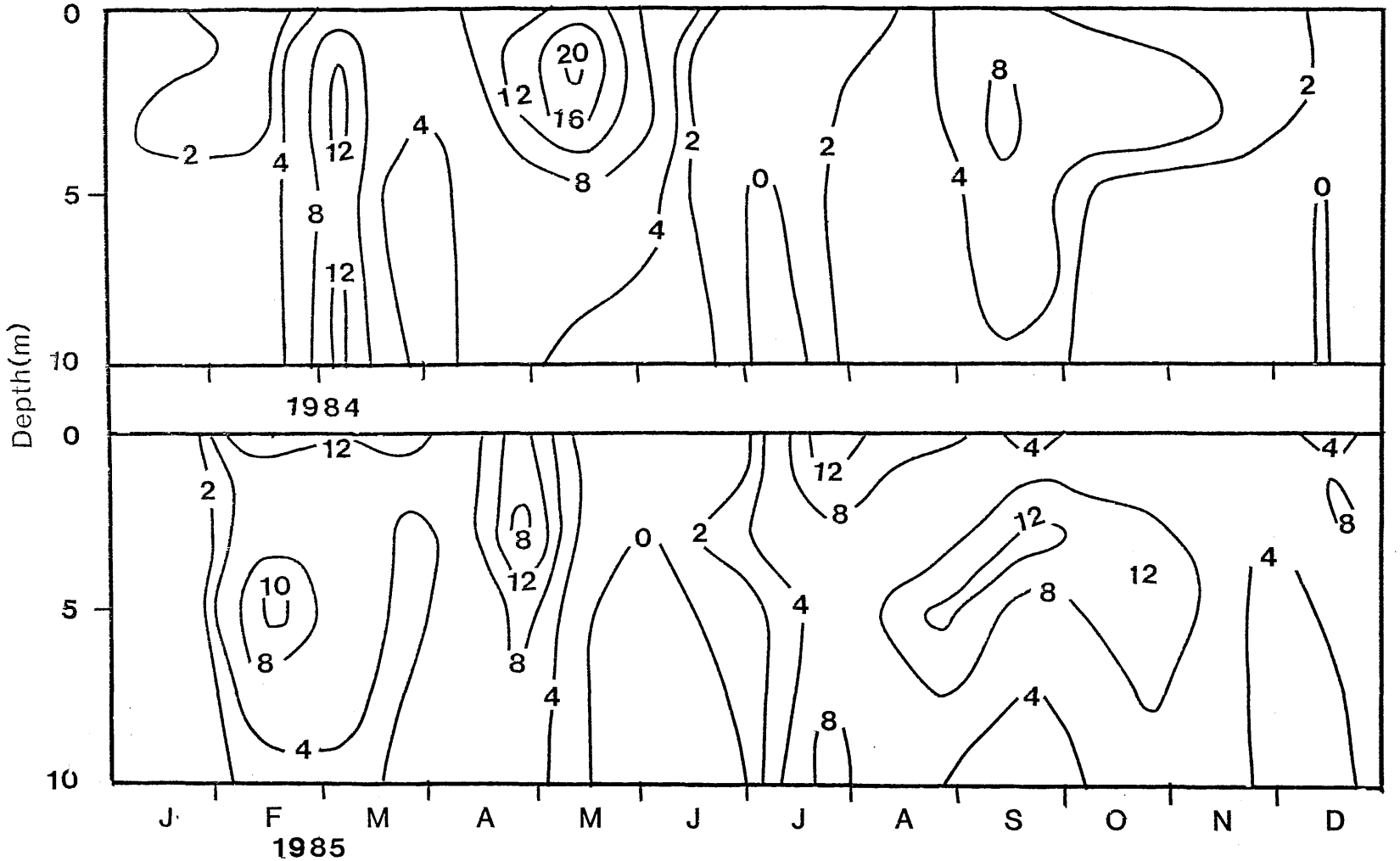
4.3.3.9. Eunotia lunaris :

Eunotia lunaris, another diatom normally considered to be benthic were also common in the plankton community throughout the water column in Dubh Lochan but the populations were comparatively lower than Eunotia pectinalis. It showed two peaks, one in spring and the other in late summer to early autumn in both the years (Fig. 32).

In 1984, a gradual increase from January lead to its spring maximum in late April to early May and the populations were uniformly distributed throughout the water column. It declined sharply in June and low levels remained up to August when the lake was thermally stratified and the nutrient levels were low. The populations increased gradually from September and reached to its second peak in late October and November with autumn overturn and mixing of

Figure 33. Seasonal variations of Frustulia rhomboides from January, 1984 to December, 1985. Isopleths are expressed as number x 100/l.

Frustulia rhomboides



the nutrients throughout the water column. This peak was slightly smaller than the spring peak and showed strong vertical stratification with highest numbers in the upper 3m water.

In 1985, the population levels during the winter and the peak in spring was similar to 1984. It declined sharply after the peak and the populations from mid May to late June were much lower than the year before. The populations from July to mid October were much higher than the previous year. It increased gradually from July and reached to its second peak in mid September. This peak was slightly higher than the autumn peak in 1984 and the highest populations were observed between 4 and 8m depth. It declined rapidly after the peak and the populations from late October to December were much lower than the year before.

4.3.3.10. Frustulia rhomboides :

Frustulia rhomboides was also common throughout the the water column during the period of study although the populations were generally low. It showed two distinct seasonal peaks in 1984 and three peaks in 1985 (Fig. 33).

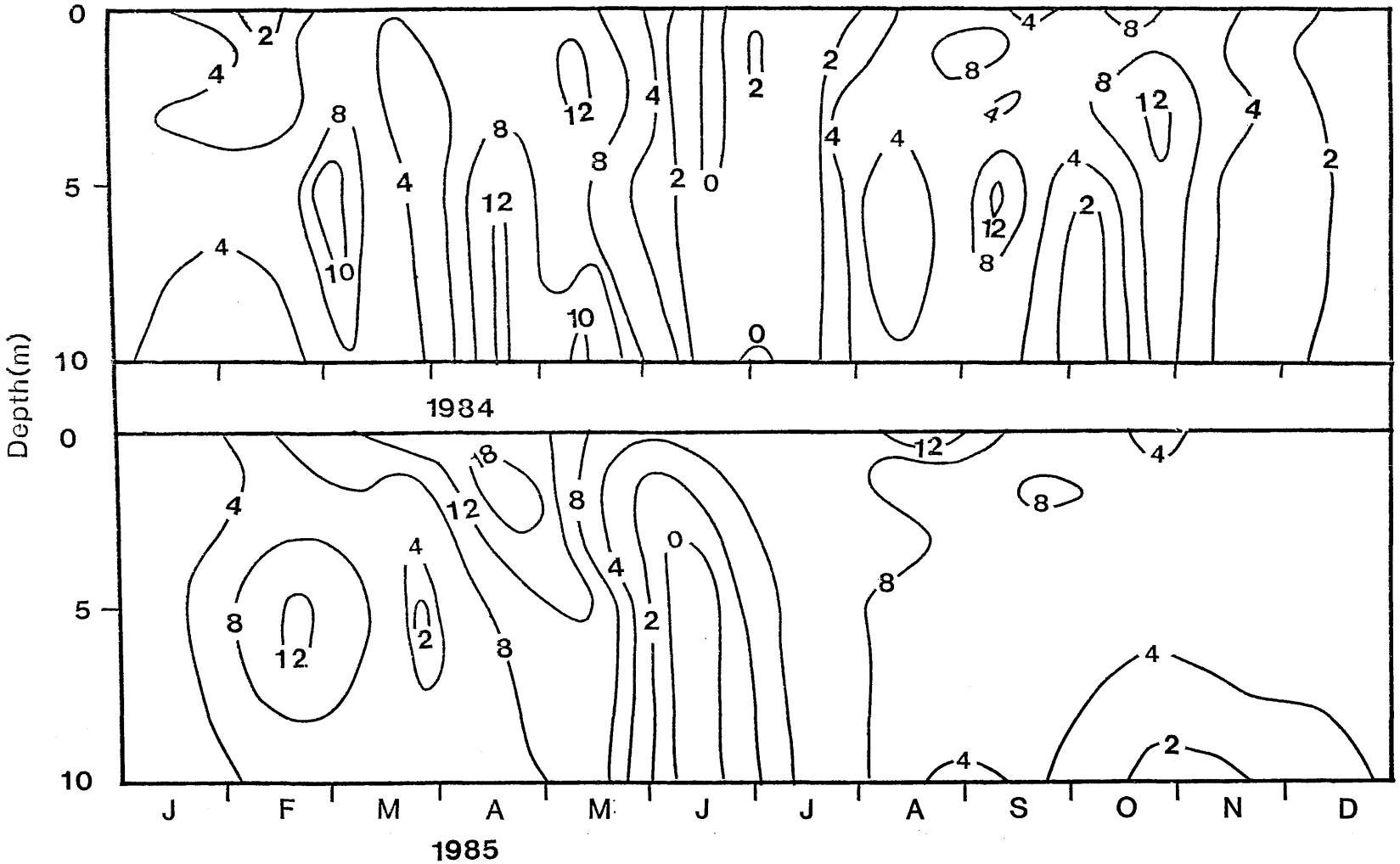
In 1984, a rapid increase from early February lead to its maximum in late February to early March. During this

peak, the populations were uniformly distributed throughout the water column. The population declined sharply in mid March and early April and again increased gradually from mid April and reached to its second peak in mid May. During this peak, strong vertical stratification was observed and the populations were confined to upper 5m water. The populations declined sharply in early June and low numbers remained from mid June to August when the lake was thermally stratified and the nutrient concentrations were low. It increased slightly in September and early October and showed slight vertical stratification with highest numbers between 2 and 5m depth. The population declined in mid October and low numbers remained up to December.

In 1985, the winter peak occurred about three weeks earlier than the year before and was similar in size to its counterpart in 1984. The populations from July to early November were much higher than the year before. It increased from July and reached to its third peak during August and October. This peak was slightly smaller than the spring one but bigger than the winter peak and the highest populations were observed between 3 and 7m depth. The populations from November to December were comparatively higher than the year before.

Figure 34. Seasonal variations of Tabellaria flocculosa from January, 1984 to December, 1985. Isopleths are expressed as number x 100/l.

Tabellaria flocculosa



4.3.3.11. Tabellaria flocculosa :

Like most of the other diatoms recorded during the present study, Tabellaria flocculosa was also common but the populations were always low. It showed three distinct seasonal peaks in both the years during winter, spring and late summer to early autumn respectively (Fig. 34).

In 1984, a gradual increase from January lead to its winter peak in late February to early March with maximum populations between 4 and 8m depth. The populations declined from mid March to early April and again increased rapidly from mid April resulting its spring maximum in late April to mid May. This peak was slightly bigger than the winter one but the populations were uniformly distributed throughout the water column. After the peak, the populations declined rapidly and disappeared from mid June to mid July. It appeared again in late July and a gradual increase from early August lead to its autumn peak in late October immediately after the autumn overturn. This peak was similar to spring one in size but the populations were comparatively higher from 2m below the surface. The populations declined sharply after the peak and low levels remained from mid November to December.

In 1985, the winter peak was slightly bigger in size

and the vertical distribution pattern was similar to 1984. The spring peak was slightly bigger but it showed strong vertical stratification with maximum populations in the upper 5m water. The third peak occurred in late August but the populations were confined in the upper part of the epilimnion. The populations during the whole autumn were much lower than the year before.

4.3.4. Diatom discussion :

Hutchinson (1967) reported that diatoms are the most important component of freshwater phytoplankton. In the present study they are only a small portion of the phytoplankton. The species composition (Table 5) suggests that most of the diatoms are littoral or benthic in origin although they were common in the plankton in Dubh Lochan. Benthic diatoms are also common in plankton in Loch Lomond (Maulood & Boney, 1980) but the species composition is quite different from Dubh Lochan. The most commonly occurring species of diatoms in Loch Lomond are Fragillaria crotonensis, Asterionella formosa, Tabellaria fenestrata, T. flocculosa, Melosira italica and Cyclotella comta where as in Dubh Lochan, these species are either absent or very rare. The most commonly occuring species of diatoms include Eunotia pectinalis, E. lunaris, Peronia herebaudi, Tabellaria flocculosa and Frustulia rhomboides. However, the

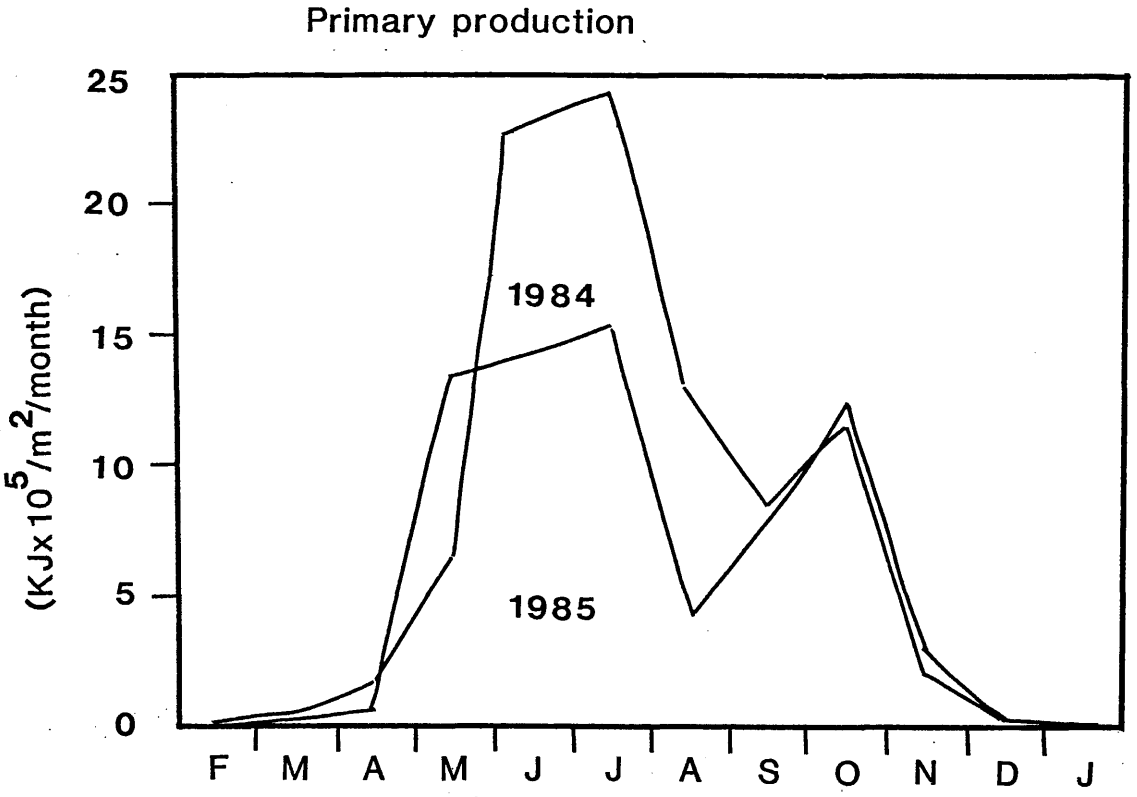
diatoms in the plankton in Dubh Lochan could possibly come from either continuous subsidy from littoral area or by reproduction throughout the water column which is unusual for these species. As there is no direct evidence of reproduction of diatoms throughout the water column, it was therefore, concluded that they must have been washed away from the littoral area. Both wind induced turbulance and increased bouyancy caused by bubbles of photosynthetically produced oxygen were probably responsible for the movement of littoral and benthic diatoms in to the plankton.

In Dubh Lochan, diatoms were more common in the present study than that of Klarer's (1978) which could be related with comparatively higher concentrations of silicate and nitrate. During the present investigation, silicate, nitrate and conductivity were generally more than twice as much as was observed by Klarer (1978). However, other physico-chemical parameters may also be partly responsible.

In the present study, most of the diatoms showed three distinct seasonal peaks in winter, spring and late summer to autumn respectively. The winter peak could be related with highest concentrations of silicate (Figs. 19 & 20) and moderately high concentrations of nitrate (Figs. 13 & 14) and orthophosphate (Figs. 17 & 18). The spring maximum is associated with the highest concentrations of nitrate and

silicate along with increased illumination (Table 1). The autumn peak, immediately after the overturn is associated with high concentrations of the nutrients especially orthophosphate and silicate. Diatoms are generally considered to be cold water species (Hutchinson, 1967). Two types of theories exhist in controlling the seasonal succession of diatoms : (1) Theory of thermal control and (2) Theory of chemical control. Many eminent investigators, notably Wesenberg - Lund (1904); Kofoid (1908); Ruttner (1937 b); and Findenegg (1943b) recognized the importance of temperature in controlling the seasonal cycle of diatoms. A contrary view expressed by other investigators of equal experience, among whom Pearsall, the main proponent of the theory of chemical control, is the most important. Pearsall (1923) emphasized the extreme variability of the temperature relations of particular species studied in a wide range of localities. Hutchinson (1967) concluded that the effect of temperature may be indirect, acting in different ways on different biological communities in regulating competition. The apparent dependence on temperature may be illusionary, the real independent variables being light or chemical parameters correlated with temperature. Lund (1949a, b; 1950a, b; Lund et al., 1963) suggested that increased illumination along with high concentrations of silicate and other nutrients together control the seasonal periodicity of diatoms. The present study is in agreement with the later

Figure 35. Monthly mean primary production from February, 1984 to January, 1986. Primary production is expressed in KJ x 10^5/ m^2 lake surface/month.


Primary production
25
20
15
10
5
0
(KJx10^5/m^2/month)
1984
1985
F
M
A
M
J
J
A
S
O
N
D
J

contention. During summer, when the availability of light is high, the minimum growth of diatom could be due to the depletion of nutrients and competition with other algal species (Hutchinson, 1967).

4.3.5. Primary production :

Primary production varied greatly between the two years but the seasonal distribution patterns were similar (Fig. 35).

In 1984, primary production ranged from 0.05 X 10^5 to 24.49 X 10^5 KJ/m^2/month and showed two distinct seasonal peaks, one in July and a second smaller one in October. The production level was very low from February to April. It increased to 6.74 X 10^5 KJ/m^2/month in May and then a very rapid increase in June (22.73 X 10^5 KJ/m^2/month) lead to the highest level (24.49 X 10^5 KJ/m^2/month) in July. Primary production declined rapidly in August (13.23 X 10^5 KJ/m^2/month) and September (8.64 X 10^5 KJ/m^2/month) and then increased to the second peak in October (11.26 X 10^5 KJ/m^2/month). It declined rapidly in November (2.00 X 10^5 KJ/m^2/month) and a gradual decline through December lead to the lowest level (0.05 X 10^5 KJ/m^2/month) in January, 1985.

In 1985, primary production ranged from 0.04 X 10^5

Table 6. Production profile throughout the water column at the time of maximum photosynthesis (14.7.1984).

Depth (m)	Primary production ($KJ/m^2/hour$)	Percentage
Surface	29498.2	19.89
1	35956.1	24.25
2	29072.4	19.70
3	22199.4	14.90
4	14106.5	9.50
5	6013.9	4.05
6	4481.4	3.02
7	3201.2	2.15
8	2347.4	1.59
9	1820.2	0.86
10	132.3	0.09

KJ/m^2/month to 15.29 x 10^5KJ/m^2/month and also showed two distinct seasonal peaks, one in July and the other in October. The production level was also very low from February to April. It increased very rapidly in May (13.76 X 10^5 KJ/m^2/month) and then a slight increase through June lead to the highest level (15.29 X 10^5 KJ/m^2/month) in July. Primary production declined very rapidly in August (4.29 X 10^5 KJ/m^2/month) and then a gradual increase through September lead to the second peak in October (12.32 X 10^5 KJ/m^2/month). It declined very sharply in November (2.92 X 10^5 KJ/m^2/month) and then a gradual decline through December lead to the lowest level (0.04 X 10^5 KJ/m^2/month) in January 1986.

The production profile at a time of maximum penetration of sun light and primary production throughout the water column is presented in Table 6. It was observed that 92.29% production occurred in the top 5m and only 7.71% in the bottom 5m water.

Klarer (1978) studied the primary production in Dubh Lochan on an weekly basis and reported three peaks of very high values during late March (151.16 X 10^5 KJ/m^2/month), late July (16 X 10^5KJ/m^2/month), and in September (74.9 X 10^5 KJ/m^2/month) respectively. However, the monthly average values were higher from February to April but from May to

October they were much lower (1.62 X 10^5 KJ/m^2/month) than the present study. On an annual basis primary production level in the present study was 92.353 X 10^5 KJ/m^2/year in 1984 and 72.271 X 10^5 KJ/m^2/year in 1985. This latter is about twice Klarer's (1978) value (36.07 X 10^5 KJ/m^2/year).

However, primary production levels observed in the present study are well within the range reported from other temperate oligotrophic lakes. Jonasson (1979) compared the levels of primary production from 11 temperate lakes including Loch Leven (160.9 X 10^5 KJ/m^2/year) in Scotland and the values ranged from 6.0 X 10^5 KJ/m^2/year to 183.1 X 10^5 KJ/m^2/year.

Primary production closely followed phytoplankton biomass (Fig. 23). In 1984, rapid increase in primary production in May coincides with increasing phytoplankton biomass. During this period phytoplankton was dominated by green flagellates and Sphaerocystis schroeteri. During the highest peak of primary production in June and July, phytoplankton biomass also reached to the highest level and the dominance was shared by Sphaerocystis schroeteri, Dinobryon divergens, Oocystis spp., and Cryptomonas spp. During the second and minor peak in October, phytoplankton was again dominated by green flagellates. In 1985, very

rapid increase in primary production in May was contributed by high production of Dinobryon divergens and Cryptomonas spp. The highest primary production in June and July was due to rapid growth of Sphaerocystis schroeteri, Oocystis spp., and Cryptomonas spp. During the second peak in October, phytoplankton was dominated by green flagellates and Cryptomonas spp.

Although the seasonal patterns of primary production in both the years were similar, the levels during June and July were much higher in 1984 than in 1985 which could be mainly due to high input of incident light energy. Although the incident light energy was not measured during the present study, the average sunshine hours data (Table 1) indicate that the incident light energy from July to September were much lower in 1985 than the year before. Low sun shine hours was due to cloud cover indicated by high rainfall in 1985 where as in 1984 the sun shine hours were much higher and the rainfall was very low during the whole summer. Seasonal variations of solar light input is not only the major reason for seasonal changes in primary production. Other factors of importance are temperature, nutrient availability, species composition, total biomass and turbulance mixing (Westlake, 1980). Moss (1982) reported that a wide range of substances are required for phytoplankton growth, among which phosphate and nitrate have been most frequently identified by workers

as limiting nutrients in temperate lakes. In the present study, phosphate concentrations were always very low. Nitrate concentrations were high prior to the highest level of primary production in late spring to mid summer in both the years. Westlake (1980) reported that photosynthetic efficiency of different species of algae varies greatly depending on the nutrient, light and temperature requirements. Although the concentrations of key nutrients were low during the whole summer, high primary production during this period were contributed mainly by green algae which can flourish in nutrient poor water (Hutchinson, 1967) when the incident light energy is high. The minor peak of primary production was confined in October just after the autumn overturn in both the years. This peak is likely to be related with increased nutrient levels especially phosphate at a time when the incident light energy was declining. The rapid decline of primary production after the autumn peak and very low levels from December to February may have been a reflection of the increasing importance of light as limiting factor (Moss, 1973). In temperate regions, an early spring peak of primary production is frequently observed due to high production of diatoms which need fairly high concentrations of nutrients (Hutchinson, 1967). In the present study, no early spring peak in primary production was recorded which could be due to low concentrations of nutrients although diatom production increased slightly.

CHAPTER — 5.

ZOOPLANKTON AND SECONDARY PRODUCTION

5.1. Introduction :

Zooplankton in general and Rotifers, Copepods and Cladocerans in particular are the largest groups of organisms in the plankton community in Dudh Lochan. They are the major direct consumers of phytoplankton, grazing on a wide variety of species (Hutchinson, 1967; Porter, 1973, 1975).

They play important role in the energy transfer process in aquatic ecosystems in secondary level. Klarer (1978) studied the plankton in Dubh Lochan and the energy flow from phytoplankton to zooplankton were assessed. The main purpose of the present study is to follow the energy flow from phytoplankton through seston to the sediment. Zooplankton was only considered in so far as it is another destination, although after their death and decomposition, they also join seston and sediment.

Two general kinds of approaches for secondary production measurements were suggested by Edmondson &

*Although the whole sample was scanned for zooplankton enumeration, the contents of 1l water is probably too low to represent the sparse population of Copepods and Cladocerans. No effort was made for a representative sample because this is another destination of energy flow and not the major aim of the present study.

Winberg (1971), through population dynamics and the physiological approach. Because of the problems of accurate measurement of secondary production due to its complex nature, the population dynamics approach was considered in the present study. Thus the zooplankton biomass (number/l) along with the seasonal patterns of individual species are reported in this chapter.

5.2. Materials and Methods :

Zooplankton were counted using the same samples collected for phytoplankton enumeration every fortnight at station 1, from surface, 1m, 3m, 5m and 10m depth between January, 1984 and December, 1985. The detail procedure for the preparation of the samples has already been described in the materials and methods section in Chapter 4 (Phytoplankton and primary production). The whole bottom area of the counting chambers were scanned under a low magnification (20x) using an inverted microscope and the final calculations were expressed as number/l. *see opposite.

Copepods were identified according to Harding & Smith (1974). Cladocerans were identified according to Scourfield & Harding (1966). Rotifers were identified according to Pontin (1978) and Ruttner - Kolisko (1974). The identifications were normally checked by Dr. R. Tippett.

Table 7. Species composition and abundance of zooplankton in Dubh Lochan.

Number	Abundance	Species
		Phulum : Arthropoda
		Class : Crustacea
		Order : Copepoda
1	+	Acanthocyclops latipes Lowndes
2	+	Diacyclops longuicloides hypnicola Gurney
3	+	Eucyclops serrulatus Fisher.
4	+	*Halicyclops aequordus Fisher.
5	+	Paracyclops fimbriatus Fisher.
6	A	Eudiaptomus gracilis Sars.
		Phylum : Arthropoda
		Class : Crustacea
		Order : Cladocera
7	+	Alona costata Sars.
8	+	A. guttata Sars.

9	+	Alonella excisa Fisher.
10	+	*A. exigua Lilljeborg
11	+	Alonopsis elongata Sars.
12	+	*Anchistropus emarginatus Sars.
13	+	Bosmoina coregoni Baird
14	+	Ceriodaphnia quadrangula O.F. Muller
15	C	*C. reticulata Jurine
16	+	*Chydorus latus Sars.
17	+	*C. ovalis Kurz.
18	+	Daphnia hyalina var. lacustris Sars.
19	+	Diaphanosoma brachyurum Lieven
20	+	Eurycercus lamellatus O.F. Muller
21	+	Holopedium gibberum Zaddach

Phylum : Aschelminthes

Class : Rotifera

22	+	Asplanchna priodonta Gosse
23	+	Asplanchnopus multiceps Schrank.
24	+	Ascomorpha ecaudis Perty
25	+	*A. ovalis Carlin
26	+	A. saltans Bartsch.
27	+	Conochilus unicornis Rousselet
28	+	Epiphanes macrourus Daday
29	+	E. senta Muller
30	+	Euchlanis dilatata Ehr.

31	+	Filinia terminalis Plate
32	+	*Gastropus sp.
33	C	Kellicottia longispina Kellicott
34	+	Keratella cochlearis Gosse
35	C	K. quadrata Muller
36	+	K. quadrata var. curvicornis Ehr.
37	+	K. quadrata var. testudo Ehr.
38	+	K. quadrata var. valgoides Edm. & Hutch.
39	+	K. serrulata var. curvicornis Rylor
40	+	Lecane logona Dunlop
41	+	*L. lunaris Ehr.
42	+	L. polenensis M. Voight.
43	+	L. rhenana Hauer.
44	+	L. saginata Harr. U. My.
45	+	*Lecane sp.
46	+	Lepadella ovalis Muller
47	+	Monommata longiseta Muller
48	+	Monostyla lunaris Ehr.
49	+	Platyias quadricornis Ehr.
50	+	Ploesoma hudsoni Imhof.
51	+	P. truncatum Lavender
52	C	Polyarthra vulgaris Carlin
53	+	*Synchaeta oblonga Ehr.
54	+	S. pectinata Ehr.

55	+	Trichocerca longiseta Schrank
56	C	T. similis Wierzejski
57	+	Trichotria tetractis Ehr.

A represents abundant : Occur in more than 90% of the samples and often represents more than 25% of the community.

C represents common : Occur in between 33% and 66% of the samples, sometimes represents more than 10% of the community.

F represents faithful : Occur in more than 66% of the samples but never represent more than 1% of the community.

R represents rare : Occur in between 33% and 66% of the samples but never represent more than 1% of the community.

+ represents present : Occur in less than 33% of the samples and never represent more than 1% of the community.

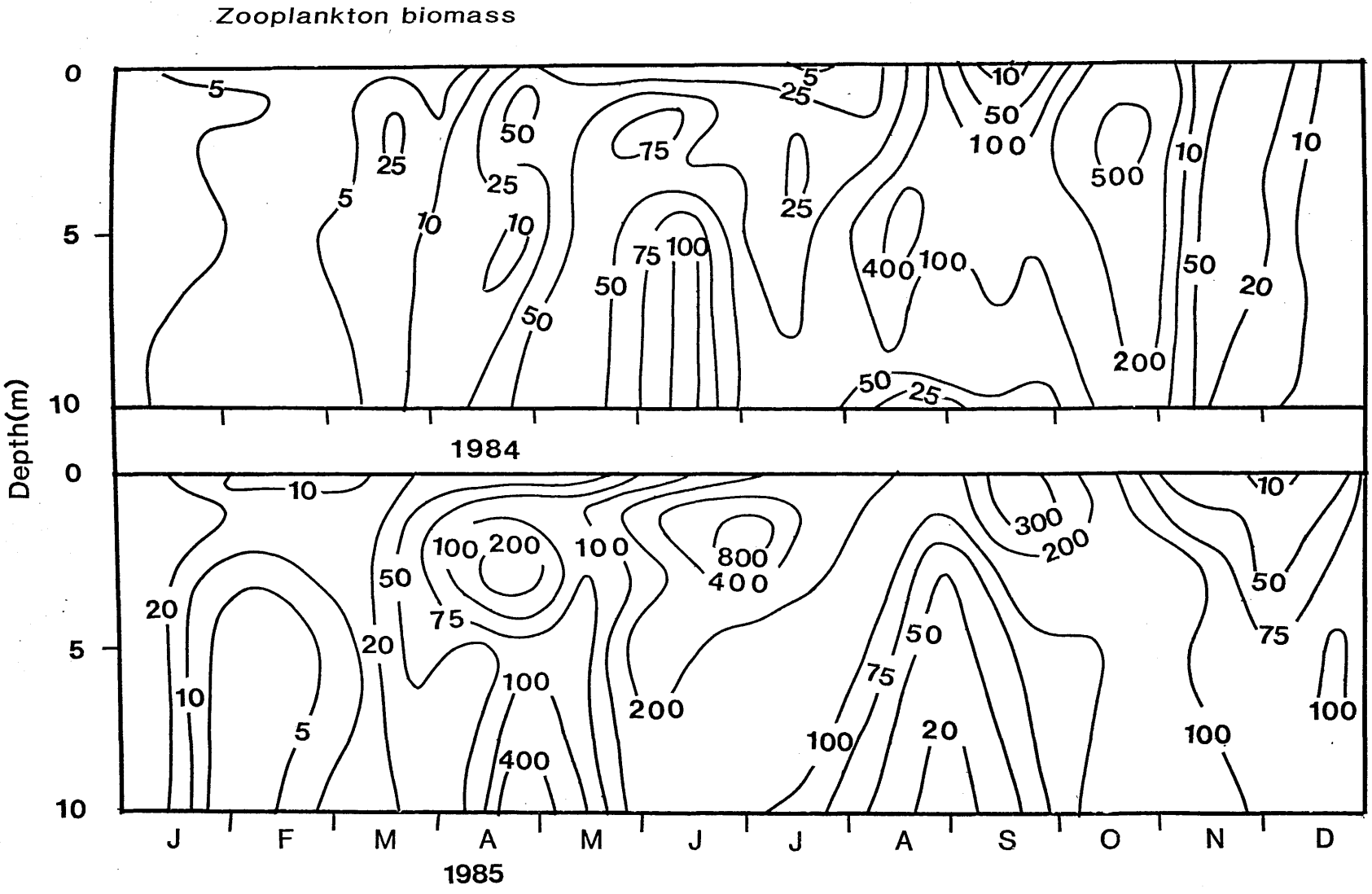
5.3. Results and Discussion :

5.3.1. Species composition :

A total of 57 species of zooplankton were identified in the present study. A list of the species along with their abundance are presented in Table 7. Among zooplankton, there were 6 species of Copepoda, 15 species of Cladocera and 36 species of Rotifera. Although many species of Rotifera were present, only 4 species were in sufficent numbers to show distinct seasonal and vertical distribution patterns.

Klarer (1978) reported 50 species of zooplankton in Dubh Lochan. The present study adds 1 species of Copepoda, 5 species of Cladocera and 5 species of Rotifera to the exhisting species list of zooplankton. The newly recorded species are presented with an asterisk mark (Table 7). One species of Copepoda, 2 species of Cladocera and 1 species of Rotifera which were recorded earlier were not observed in the present study.

Figure 36. Seasonal variations of zooplankton biomass from January, 1984 to December, 1985. Isopleths are expressed as number/l.


Zooplankton biomass
Depth(m)
0
5
10
1984
1985
J
F
M
A
M
J
J
A
S
O
N
D

5.3.2. Zooplankton biomass (expressed as number/l) and community patterns :

Zooplankton biomass showed distinct seasonal and strong vertical distribution patterns (Fig. 36). It showed three distinct seasonal peaks with considerable variations between the two years.

In 1984, zooplankton biomass was very low in January and February. A gradual increase from mid March resulted an early summer peak in mid June when the lake was thermally stratified and the surface water temperature was about 18°C. During this peak, highest populations were recorded between 5 and 10m depth. The biomass declined gradually in July and increased suddenly to its second peak in mid August when the surface water temperature was approximately 20°C and the oxygen saturation in the hypolimnion was very low. This peak was about 4 times bigger than the earlier one in June and showed strong vertical stratification with highest numbers in the middle of the water column between 3 and 8m depth. From late August to mid September, it declined slowly before increasing rapidly in October resulting in a third and highest peak when the water was isothermal and the temperature was about 11°C. The biomass declined sharply throughout the water column in November

and reached to its lowest level in December.

In 1985, zooplankton biomass in January and February were comparatively higher than the year before and showed strong vertical stratification with maximum numbers between 1 and 3m depth. A gradual increase from mid March lead to its spring maximum in mid April and early May. During this peak, the biomass was high from 2 to 5m depth and the highest numbers were observed between 8 and 10m depth in the hypolimnion as in the year before. After the spring maximum, it declined slowly in mid May and from early June, a rapid increase resulted a second maximum in late June and early July with highest numbers in the epilimnion. The biomass declined gradually from late July to August and then a rapid increase from early September lead to a third maximum in late September. During this peak, it showed strong vertical stratification with highest numbers in the upper 2m water. During the whole summer, the biomass in the upper waters were higher than the bottom waters. Hypolimnetic biomass during anoxic condition in late July and August decreased sharply while the epilimnetic biomass remained high. No autumn peak was observed in 1985 but the numbers in November and December were much higher than the year before showing strong inverse stratification with maximum numbers from 5 to 10m depth.

The spring peak in 1985, coincided with the highest

production of spring diatoms. The early summer peak coincides with highest production of phytoplankton biomass (Fig. 23) including peaks of several species namely Sphaerocystis schroeteri (Fig. 24), Dinobryon divergens (Fig. 25). Oocystis spp., (Fig. 26) and Cryptomas spp., (Fig. 28). The late summer and autumn peak occurred at the same time as the second peak of green flagellates (Fig. 27), D. divergens, Oocystis spp., and Botryococcus braunii (Fig. 29) along with the autumn peaks of diatoms. The population of adult Eudiaptomus gracilis dominated the sparse zooplankton community during the winter months. In early spring, nauplius production increased with increasing temperature and the maturation of the nauplii in to copepodite and then adults lead to a rapid rise of the population during late May and early June. Keratella quadrata had dominated the community in March and April but was again overtaken by Eudiaptomus gracilis in May. As the populations of E. gracilis declined in early June, K. quadrata again dominated after a decline in May. In late June and early July, Kellicottia longispina and Ceriodaphnia reticulata coincided with the highest level of phytoplankton production. As these dominant species declined in number, Trichocerca similis replaced the dominance in late July and August. However, both nauplius and adult populations of E. gracilis increased to a second peak and was second in order of importance during this

time. In September and October, Polyarthra vulgaris was the dominant species followed by the nauplius of E. gracilis and K. longispina. However, C. reticulata, T. similis and K. quadrata were also observed in considerable numbers. In November and December, zooplankton populations were generally very low and no species dominated although Rotifers were comparatively higher than the other groups of zooplankton.

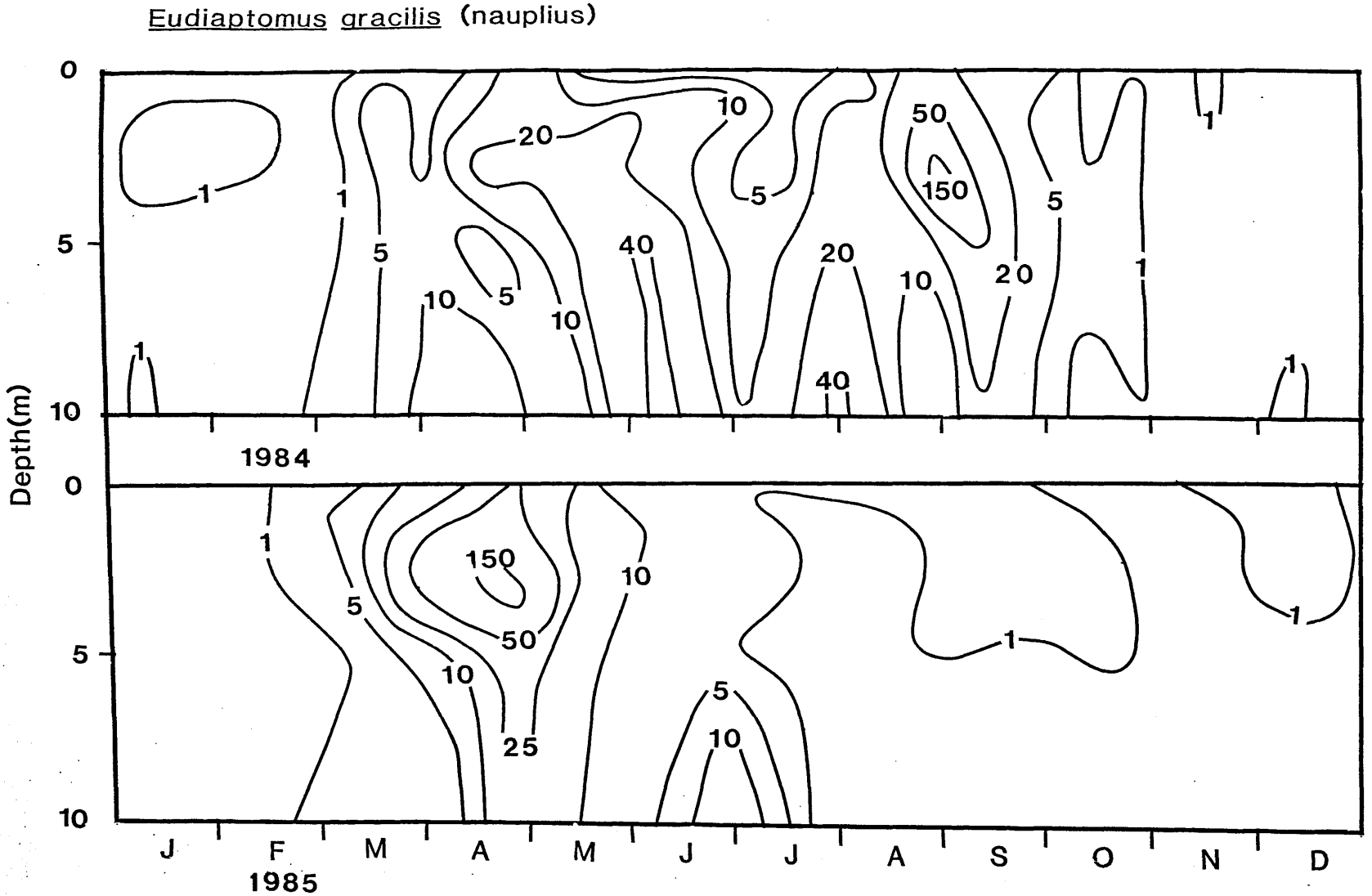
Klarer (1978) reported that Copepods dominated in winter and early spring with highest numbers of E. gracilis. During the summer months, Copepods, Cladocerans and Rotifers were present in similar numbers but Rotifers often dominated. In autumn zooplankton were reported to be very low but the Rotifers also dominated the zooplankton community.

In the present study, Copepods dominated in winter and early spring. During the whole summer, the Rotifers were dominant and in autumn the numbers of zooplankton were also low and no distinct dominant pattern could be established.

5.3.3. Individual species pattern :

Although 57 different species and varieties of zooplankton were identified in the present study, only 6

Figure 37. Seasonal variations of Eudiaptomus gracilis (nauplius) from January, 1984 to December, 1985. Isopleths are expressed as number/l.


Eudiaptomus gracilis (nauplius)
Depth(m)
0
5
10
1984
1985
J
F
M
A
M
J
J
A
S
O
N
D

species were recorded frequently enough to permit an examination of individual seasonal succession and vertical distribution patterns.

5.3.3.1. Eudiaptomus gracilis :

Eudiaptomus gracilis was the most common Copepod in the plankton of the Dubh Lochan and was present throughout the year. The patterns of egg production was not analyzed. The various naupliar stages were bulked together in the present study. Nauplii were also present throughout the year, but populations showed considerable variations between the two years (Fig. 37).

In 1984, the nauplii were very low in January and February. Numbers increased gradually from March and reached to a first maximum in early June. During this peak, maximum populations were observed in the bottom 5m water but considerable numbers were also observed in the epilimnion. The populations declined sharply in late June and early July and again increased to a second peak in late July to early August. This peak was similar in size and the maximum populations were also observed in the hypolimnion but the population level in the epilimnion was very low. It declined slightly in mid August and again increased to a third peak during late August and early September. This peak was about

4 times bigger than the earlier peaks, the highest populations were observed in the epilimnion and the numbers declined with increasing depth. After the peak, it declined rapidly in September and the populations were very low from October to December.

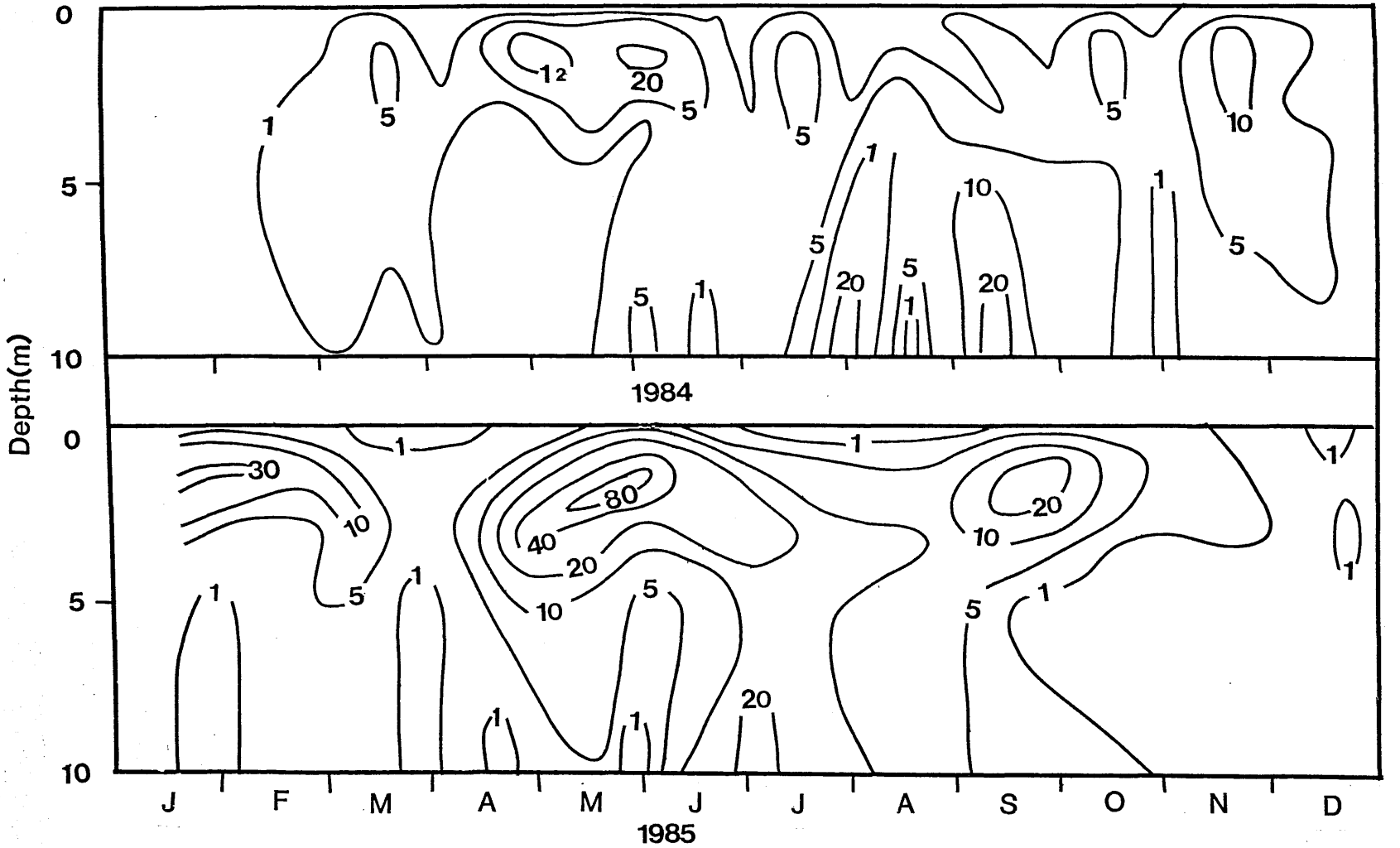
In 1985, nauplii were absent in January and February. A rapid increase from mid March resulted in peak numbers in April. At this time, the greatest populations were observed in the upper 5m water. After the peak, the populations declined rapidly in early May. From late May, it declined gradually and reached to its lowest level in late July and the same level continued through the rest of the year.

Klarer (1978) reported a single spring peak of nauplii in 1974 and 1976 and two peaks, one in spring and a second one in summer in 1975. Hutchinson (1967) reported that in Europe E. gracilis may breed throughout the year but there are often periods in which the production of eggs and nauplii are particularly intense. A spring maximum in egg and nauplii production seems to be common but there are several reports of second and third maxima during early and late summer (Gurney, 1931 ; Kuntze, 1938 and Elster, 1954).

The adult populations of E. gracilis were also present throughout the year except in January, 1984 and showed

Figure 38. Seasonal variations of Eudiaptomus gracilis (adult) from January, 1984 to December, 1985. Isopleths are expressed as number/l.

Eudiaptomus gracilis (adult)



considerable variations between the two years (Fig. 38). The highest populations were always observed in the upper few metres water except in July and September.

In 1984, populations were low in February and March. A gradual increase from April lead to its first peak in late May and early June which derived from the spring peak of nauplii (Fig. 37). During this peak, the highest populations were observed in the upper 3m water. The populations declined sharply in late June and early July. It increased rapidly in the hypolimnion in mid July and reached to a second peak in late July to early August which is due to the nauplii produced during the peak in early June (Fig. 37). At this time, the maximum populations were observed between 8 and 10m depth although the oxygen saturation (Fig. 5) in the hypolimnion was low. The populations declined sharply in August and again increased to a third peak in mid September. This peak was similar to the second peak in every respect. Afterwards, it declined sharply in late September and low numbers remained until late October and again increased slightly in November and December.

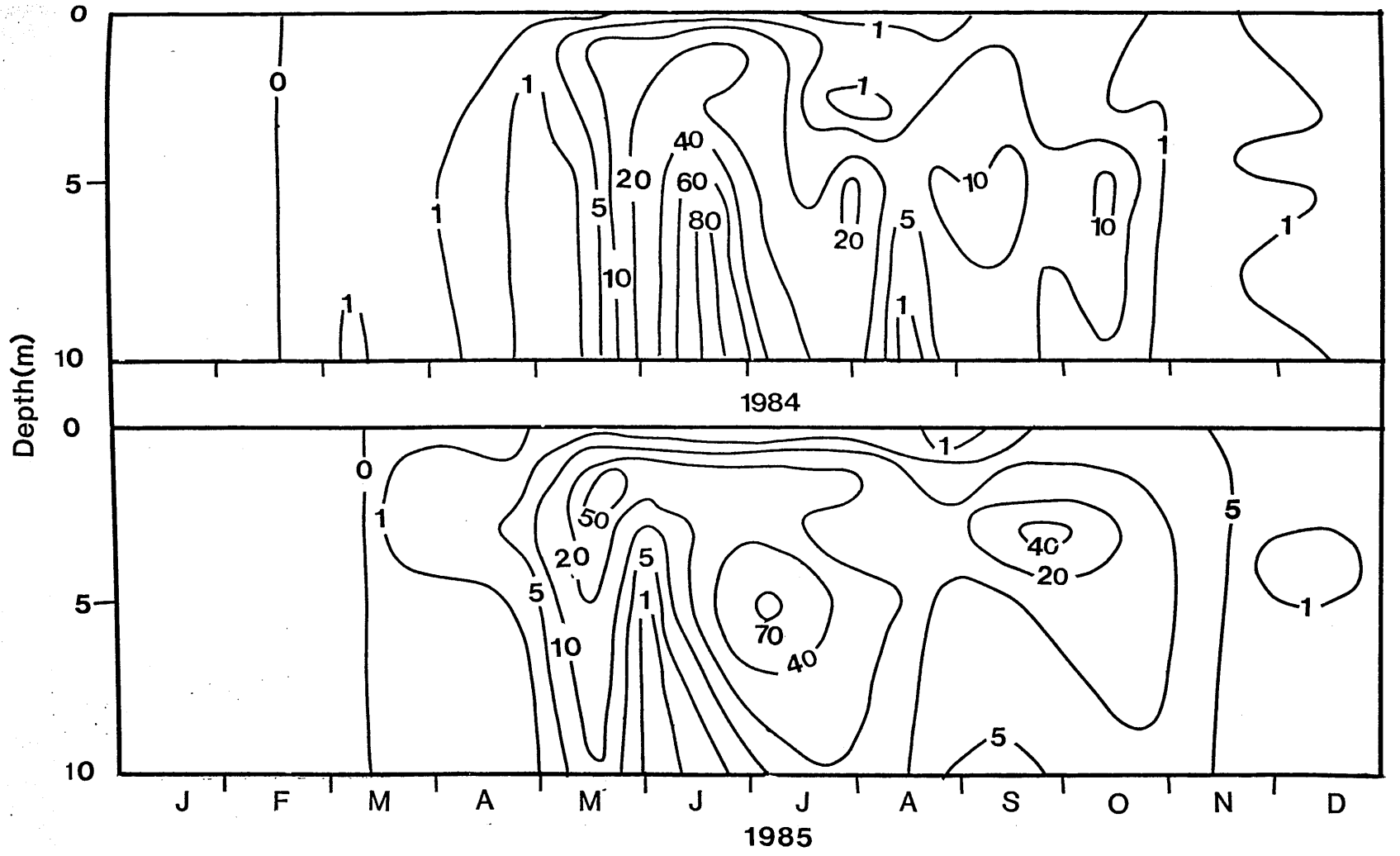
In 1985, E. gracilis showed three distinct seasonal peaks and the highest populations were generally observed in the upper 4m water. The first peak was in late January and early February which could be due to the late summer nauplii

peak in 1984. During this peak, the populations showed strong vertical stratification with highest numbers in the upper 4m water. The populations declined sharply in March and a gradual increase from May lead to its second maximum during late May and early June which is due to the maximum production of nauplii in April (Fig. 37). This peak was about 2.5 times bigger than the winter one and the highest populations were observed in the upper 5m water. After this peak, the populations declined gradually through July and August and again increased slightly in the epilimnion in September. The population level from October to December remained very low.

Klarer (1978) observed different patterns of seasonal succession of E. gracilis in his three years study period in Dubh Lochan . In 1974, it showed two maxima, one in spring and a second one in late summer, a single summer maximum in 1975 and no distinct peak in 1976 although the populations remained high. Eudiaptomus gracilis is also an important component of zooplankton in Loch Lomond with spring and summer maximum (Chapman, 1969). Hutchinson (1967) reported that in Europe, the adult populations of E. gracilis are common throughout the year but there are often periods in which the species is abundant depending on the availability of food and optimum environmental condition. However, it seems that the species shows different patterns of seasonal

Figure 39. Seasonal variations of Ceriodaphnia reticulata from January, 1984 to December, 1985. Isopleths are expressed as number/l.

Ceriodaphnia reticulata



succession in different ecosystems of temperate climate but spring and summer peaks are common and the winter and autumn peaks are rare.

In the present study, three distinct adult generations were observed in 1984 and a single generation in 1985 based on the nauplii peaks. Klarer (1978) reported three distinct adult generations of E. gracilis in Dubh Lochan but Chapman (1969) observed two adult generations in Loch Lomond. However, it can be concluded that E. gracilis populations show different seasonal succession patterns in different ecosystems and great variations may also occur in the same environment in different years and unlike other species, it is difficult to generalise.

5.3.3.2. Ceriodaphnia reticulata :

Ceriodaphnia reticulata, the most common Cladoceran species was present throughout the year except in January and February. It showed a single peak in summer in 1984 and three distinct seasonal peaks in spring, mid summer and early autumn in 1985 (Fig. 39).

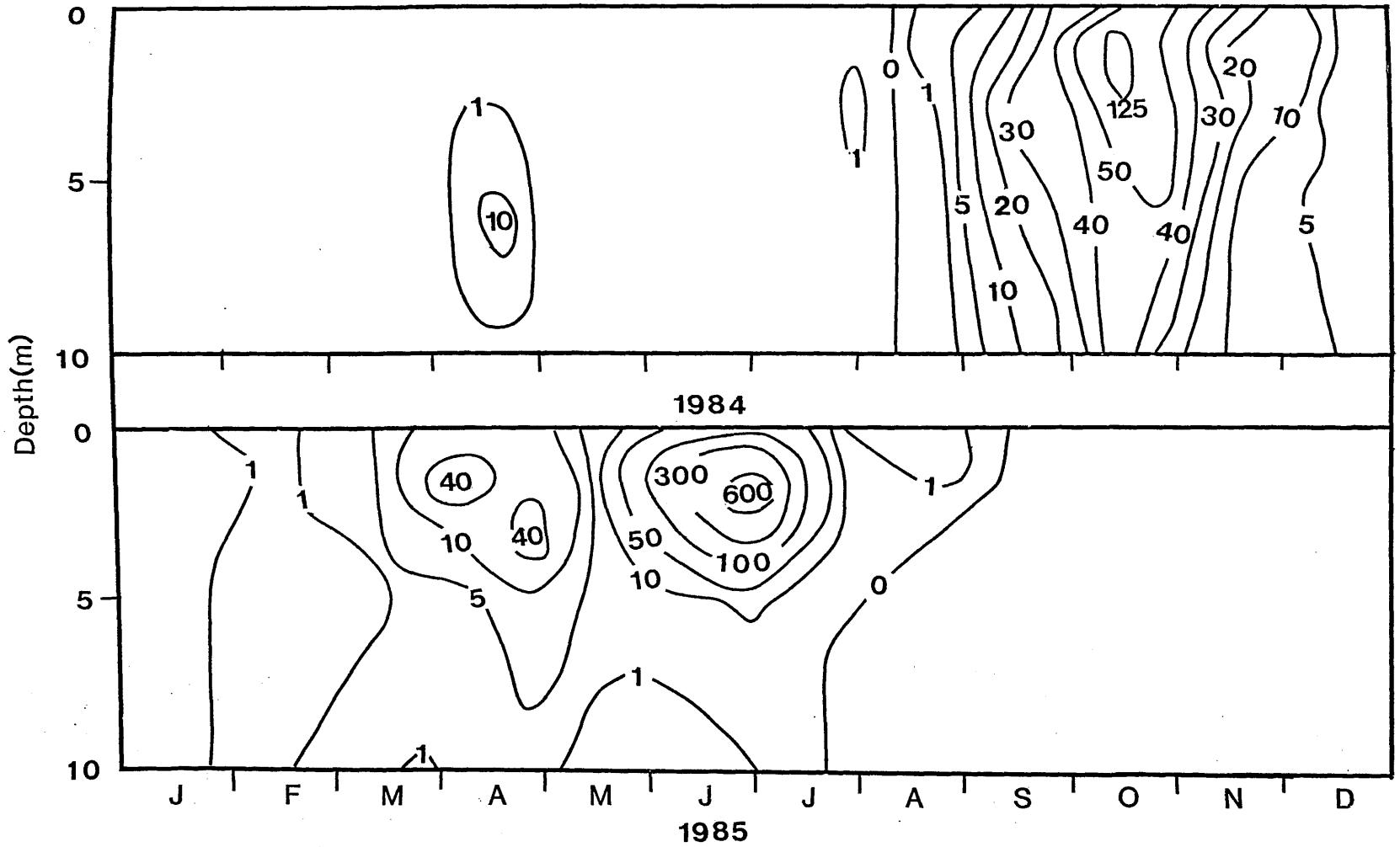
In 1984, a gradual increase from early May lead to a peak in mid June. During this peak, the populations increased with increasing depth and the highest numbers were

observed between 5 and 10m depth. After the peak, the populations declined sharply in the epilimnion and hypolimnion in late July and early August and again increased slightly in metalimnion in September and early October. The populations declined to the lowest level in mid October and low level remained up to December.

In 1985, the species also appeared in March and a sudden increase in early May resulted in the first peak in mid May. At this time, the highest populations were observed between 1 and 3m depth and declined with increasing depth. The populations declined sharply in early June and a rapid increase in late June lead to its second peak in early July. This peak was slightly bigger than the spring one and the populations were confined in the metalimnion. The populations declined gradually from late July to August and again increased to a third peak in late September. This peak was the smallest in size and the populations were confined between 2 and 5m depth. After the peak, the populations declined gradually from October and reached to the lowest level in December. However, during the whole summer, the highest populations were observed between the epilimnion and hypolimnion. During the period of hypolimnetic anoxia, the populations were low in the bottom waters but never disappeared.

Figure 40. Seasonal variations of Kellicottia longispina from January, 1984 to December, 1985. Isopleths are expressed as number/l.

Kellicottia longispina



Klarer (1978) did not observe C. reticulata in Dubh Lochan. He reported C. quadrangula as the dominant species among Cladocerans. In the present study, C. quadrangula was present occasionally and only in small numbers. However, the two species are taxonomically very distinct and the possibility of error in identification is slight. The claw of C. reticulata has a prominent comb of 3 to 7 coarse teeth near the base but the claw of C. quadrangula is without such a comb. Hutchinson (1967) concluded that the Ceriodaphnia in general is more characterestic of ponds rather than lakes. Findenegg (1953) and Pejler (1961) reported that Ceriodaphnians were widely distributed summer form in small lakes which agrees with the present study.

5.3.3.3. Kellicottia longispina :

Kellicottia longispina was one of the commonest planktonic Rotifer in Dubh Lochan. It showed a single autumn peak in 1984 and two peaks, a minor peak in spring and a major peak in early summer in 1985 (Fig. 40).

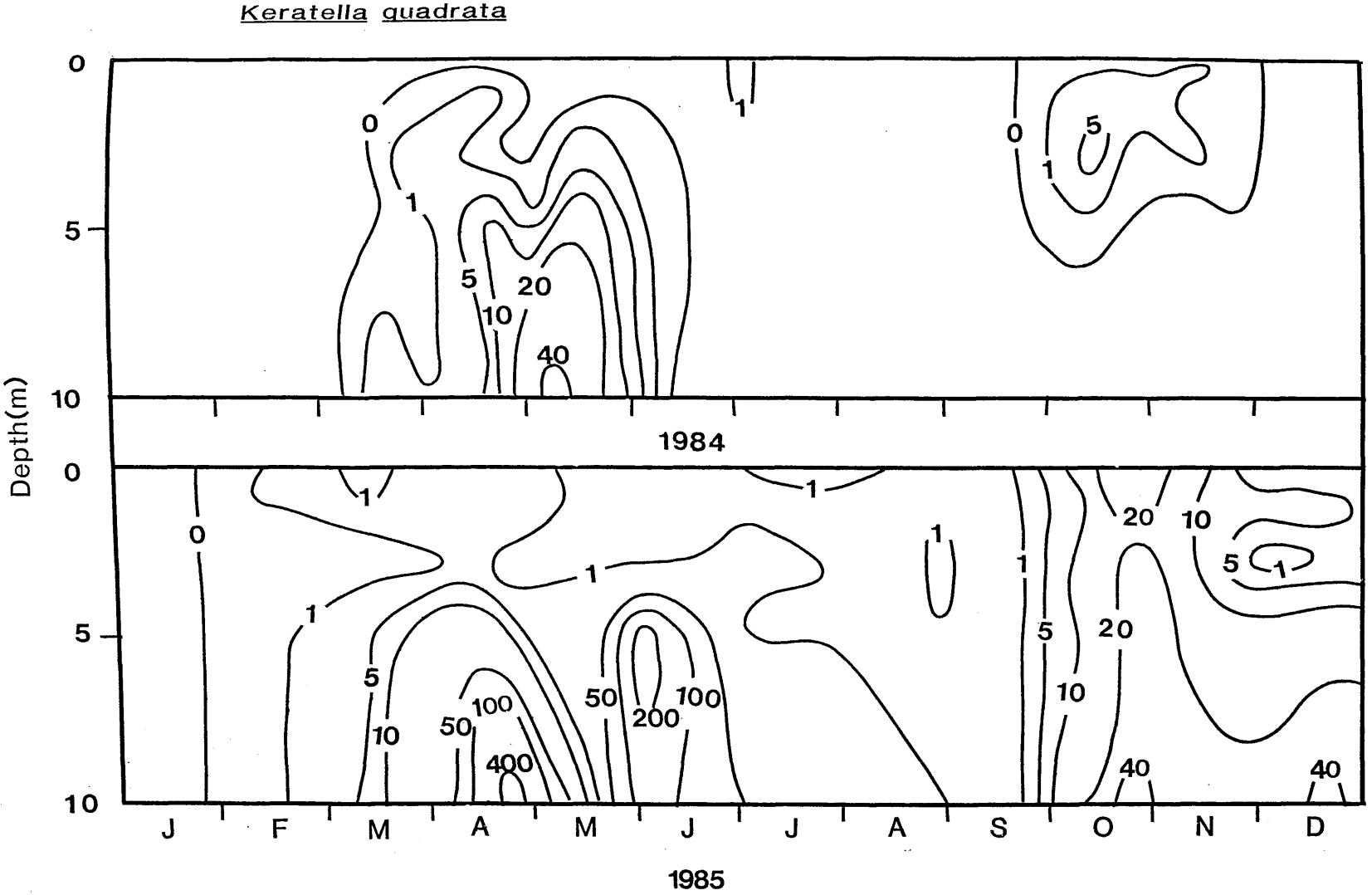
In 1984, the species first appeared in April but was absent from May to mid July. It appeared again in late July and a gradual increase from late August lead to its maximum in mid October just after the autumn overturn. During this peak, the highest populations were observed in the upper 4m

water and their numbers decreased with depth. The populations declined gradually from late October and reached to its lowest level in December.

In 1985, the species was present from January to early September. The population level in January and February was very low. A gradual increase from mid March resulted a minor peak in April. At this time, the populations were confined to the upper 5m water. It declined sharply in early May and a rapid increase from late May lead to the major peak in late June.

This peak was approximately 15 times bigger than the spring one and the populations were also confined to the epilimnion. It declined sharply in July and disappeared by early September and was absent from mid September to December. Klarer (1978) reported that the species was present throughout the year in Dubh Lochan and showed a single mid summer maximum in 1974 and 1975 and two peaks in 1976, one in early summer and the second one in late summer with no vertical stratification throughout the year. During the present study, the populations showed strong vertical stratification during the peaks and their numbers were always higher in the upper 5m water. Hutchinson (1967) categorized K. longispina as a perennial species with late spring and early summer maximum but an autumn maximum is not

Figure 41. Seasonal variations of Keratella quadrata from January, 1984 to December, 1985. Isopleths are expressed as number/l.


Keratella quadrata
Depth(m)
0
5
10
0
5
10
1984
1985
J
F
M
A
M
J
J
A
S
O
N
D

uncommon. Pejler (1957b) reported that K. longispina is characterestics of oligotrophic water and the species is most common in the summer months. Larsson (1971) reported that Kellicottia sp. was found under all oxygen and temperature conditions. Pejler (1957b) also reported that the species is sensitive to high light levels and was confined to the lower water during the summer. To the contrary, during the present study, the species always showed high populations in the upper waters, so it must be concluded that the species is not sensitive to light. Similar observations were also made by Klarer (1978) in his three years study period in Dubh Lochan.

5.3.3.4. Keratella quadrata :

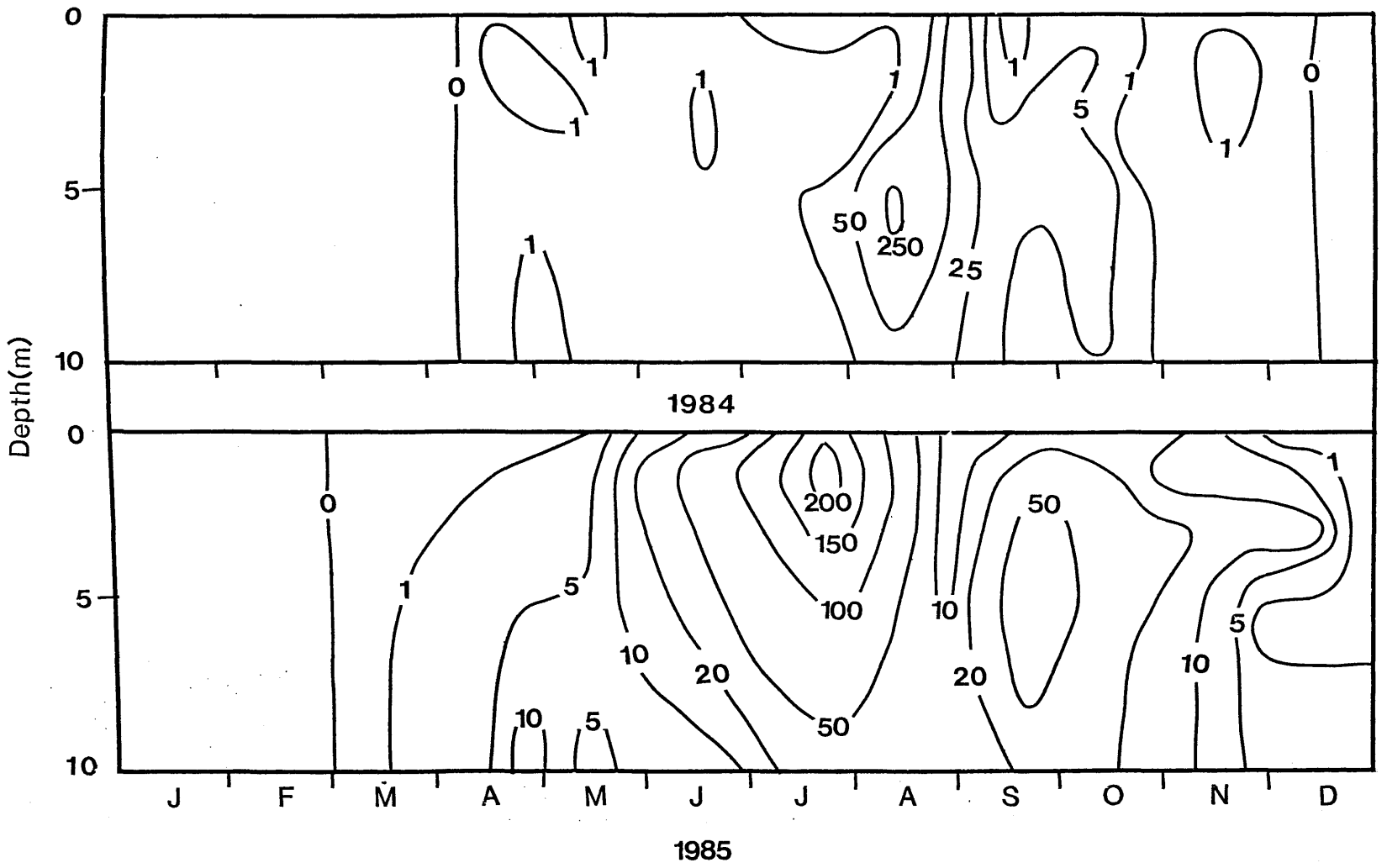
Keratella quadrata showed great variations between the two years. In 1984, it was present for a short time and showed a minor peak in spring. It was present throughout the year in 1985 and showed two distinct peaks in spring and early summer (Fig. 41) respectively.

In 1984, the species was absent in January and February. It first appeared in mid March and a gradual incease from mid April resulted in a small peak in early May. During this peak, an inverse stratification was observed with highest population at the bottom. However, the

species was absent in the upper 2m water during this time. The population declined sharply in late May and disappared by June. Keratella quadrata was absent from June to late September, it appeared again in October and was confined to the upper 4m water. A very small number remained up to mid November and again disappeared in late November.

In 1985, the species was present throughout the year except in January. During spring and summer, the populations were generally very low in the upper 4m water. However, the populations increased gradually from March and reached to its spring peak in late April. This peak was approximately 10 times bigger than its counterpart in 1984. The populations were confined to the lower 5m water and the highest numbers were observed at the bottom. The population declined sharply in early May and again increased to a second peak in early June. This peak was about half the size of the spring one and the highest numbers were observed between 5 and 8m depth. It declined sharply in early July and low number remained up to early September. In October, the population increased throughout the water column but in November and December, it declined in the upper 5m water and in deep water the numbers remained high. However, in both the years, the populations tend to be confined from 5 to 10m depth except in October, 1985.

Figure 42. Seasonal variations of Trichocerca similis from January, 1984 to December, 1985. Isopleths are expressed as number/l.


Trichocerca similis
Depth(m)
0
5
10
1984
0
5
10
J
F
M
A
M
J
J
A
S
O
N
D
1985

Klarer (1978) observed K. quadrata throughout the year. The populations were reported low in winter and a single peak was observed in mid summer with maximum populations at the bottom as was observed in the present study in 1985. Pejler (1957a) and Comita (1972) reported that the species is perennial with highest populations in spring to early summer. Hutchinson (1967) reported maximum population of K. quadrata during spring but Doohan (1973) observed highest populations in spring and autumn. However, in the present study, a spring peak was observed in both the years, a second summer peak was observed only in 1985 but autumn peak was never observed in Dubh Lochan. The species could be sensitive to high light level as it was always confined in the lower water.

5.3.3.5. Trichocerca similis :

Trichocerca similis showed distinct seasonal and vertical distribution patterns (Fig. 42). It showed a single summer peak in 1984 and two seperate peaks, one in mid summer and a second one in late summer in 1985.

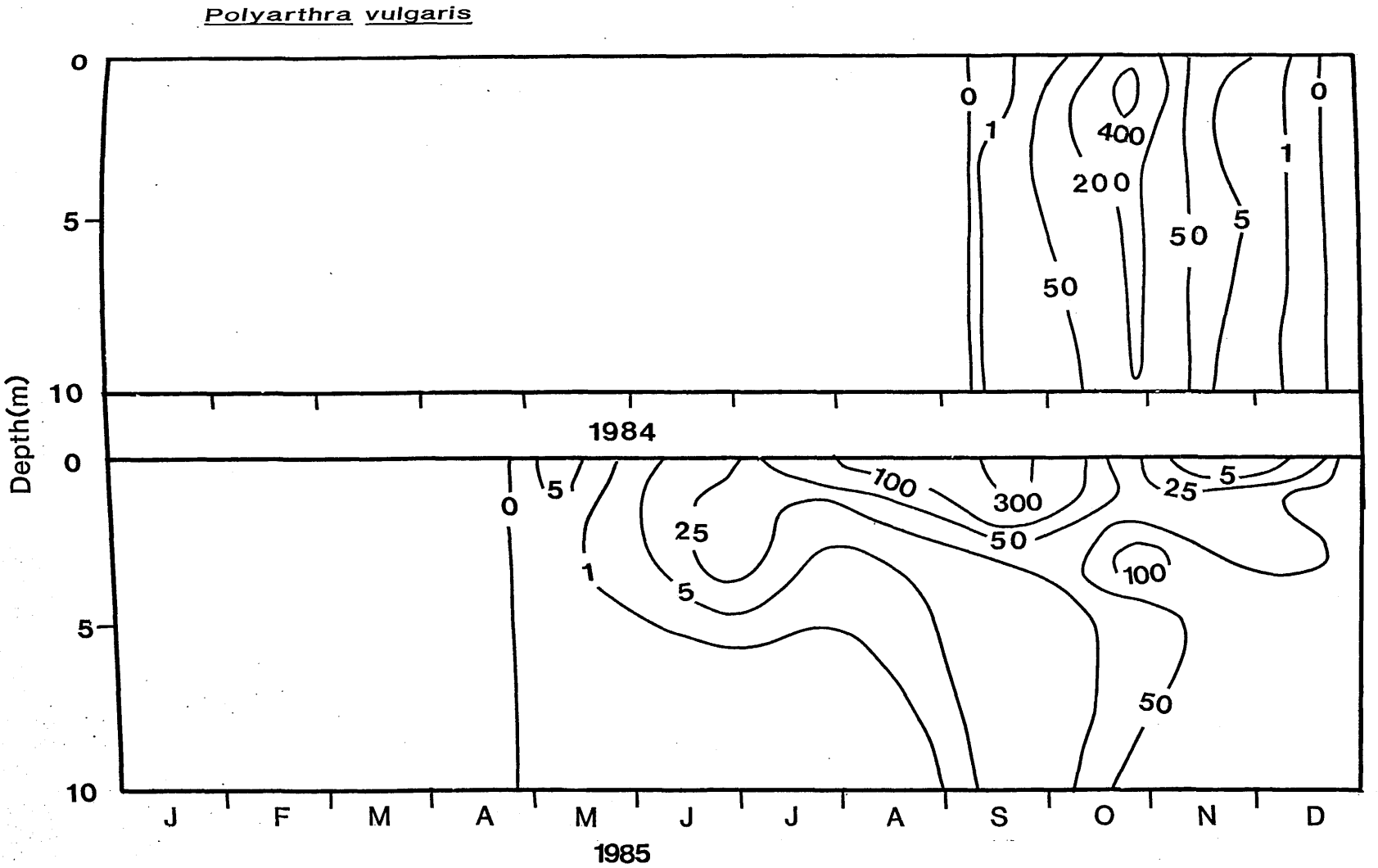
In 1984, the species was present from April to November. The populations remained very low from April to mid July. A sudden increase from late July resulted a single summer maximum in mid August. During this peak, the

populations were confined between epilimnion and metalimnion. It declined rapidly in late August and early September and reached to its lowest level in late October and November and disappeared by early December.

In 1985, the species first appeared in mid March and was present during the rest of the year. The populations increased gradually from May and reached to a summer maximum in late July. This peak was slightly smaller than its counterpart in 1984 and showed strong vertical stratification with maximum populations in the epilimnion and their numbers decreased with increasing depth. The populations declined sharply in August and again increased in September resulting a second and minor peak in late September. This peak was approximately three times smaller than the mid summer one and the highest populations were observed between 3 and 7m depth. The populations declined gradually through the autumn and reached to its lowest level in December. However, the autumn populations were comparatively higher than the year before.

Klarer (1978) recorded the species in Dubh Lochan but the populations were very low and did not show any seasonal succession in his three years study period. Hutchinson (1967) reported that Trichocerca sp. is ordinarily holoplanktonic and is an important element only in late

Figure 43. Seasonal variations of Polyarthra vulgaris from January, 1984 to December, 1985. Isopleths are expressed as number/l.


Polyarthra vulgaris
Depth(m)
0
5
10
0
1
400
200
50
5
1
0
50
1984
0
5
0
5
25
1
100
300
50
25
5
100
50
J
F
M
A
M
J
J
A
S
O
N
D
1985

summer but it may have two maxima in July and September or a single one in August. Carlin (1943) reported that Trichocerca is usually a genus of eutrophic ponds and Wesenberg-Lund (1930) concluded that Trichocerca sp., is planktonic only during a few weeks in summer.

The present study clearly indicate that the species is a summer form and the succession occurred during the period of high phytoplankton production (Fig. 23).

5.3.3.6. Polyarthra vulgaris :

Polyarthra vulgaris was present from mid September to mid December in 1984 and from March to December in 1985. It showed distinct seasonal and vertical distribution patterns (Fig. 43) with considerable variations between the two years.

In 1984, the species first appeared in mid September and a rapid increase from late September lead to its single peak in late October. The highest populations were observed in the upper 3m water and their numbers declined with increasing depth. The populations declined rapidly in November and disappared by late December.

In 1985, the species first appeared in early May. It

increased gradually through the summer and reached to its peak in mid September. This peak was slightly smaller than its counterpart in 1984. The populations declined gradually in November and December but their numbers were much higher than the year before. During summer stagnation when the oxygen concentrations in the bottom waters were low, the populations were confined in the epilimnion.

Klarer (1978) also reported a single autumn maximum of Polyarthra vulgaris in Dubh Lochan and the species was absent during winter and early spring. The populations were also confined to the epilimnion during thermal stratification in summer. Similar observations were also made by Bricker & Gannon (1976). In the present study, the species was absent from January to August in 1984 and from January to April in 1985. Pejler (1957a & b) and Hutchinson (1967) reported that P. vulgaris is a perennial species. Other workers (Hutchinson, 1967; Comita, 1972; and Doohan, 1973) reported that this species shows bimodal seasonal distribution patterns with a peak in the spring and the second peak in the autumn. However, the observations in the present study and the study of Klarer (1978) suggest that the species shows a single autumn peak and there is no sign of spring maximum in Dubh Lochan. It seems that P. vulgaris is a warm water species but temperature may not be an important criteria in determining the seasonal succession

(Hutchinson, 1967). Pejler (1957b) believed that Polyarthra sp., was sensitive to either low oxygen level or to the physical and chemical conditions associated with oxygen deficiency.

5.4. Phytoplankton -- Zooplankton relationship :

In the present study, the seasonal succession patterns of phytoplankton and zooplankton were interdependant for at least part of the year and this is best demonstrated in 1985. Hutchinson (1967) reported that the succession of phytoplankton in temperate region is primarily controlled by water temperature and light. Moreover, there is a third factor over and above temperature and light, namely the concentrations of various substances required for plant nutrition or sometimes disadvantageous to particular species. However, the interaction between phytoplankton and zooplankton may be a significant influence in determining the succession of each communities in lacustrine ecosystem. The interrelationship between phytoplankton and zooplankton is well documented (e.g. Pennington, 1941; Edmondson, 1964 and Saunders, 1969).

During winter months, light energy is not enough to support algal growth (Hutchinson, 1967) which was also

reflected by very low numbers of zooplankton in Dubh Lochan. However, in 1985, Eudiaptomus gracilis population size increased slightly which was due to the maturation of the nauplii produced in the autumn of the previous year. With rising insolation levels, green flagellates flourished in March and early April when Keratella quadrata populations were at the highest level and the nauplii of E. gracilis started to increase. In mid to late April, Dinobryon divergens dominated the phytoplankton populations and Cryptomonas spp., also reached to a spring peak. The adult populations of E. gracilis started to increase with the increase of D. divergens at a time when K. quadrata populations were also high. Previous workers (Lehman, 1976a; Patalas, 1970 and Schindler, 1972) have concluded that Dinobryon sp., is very efficiently assimilated by several species of Copepods and Cladocera. Klarer (1978) reported that the adult populations of E. gracilis were also able to assimilate Dinobryon sp., very efficiently due to their ability to accept a wide range of food particle sizes. As the populations of Dinobryon sp., increased with high population of K. quadrata, it is reasonable to conclude that this species was not a suitable source of food for K. quadrata or at least that the K. quadrata grazing was not severe enough to control the population size. Klarer (1978) also reported similar phenomena because of their general inability to utilize D. divergens as a food source. Amren

(1964) reported that Dinobryon sp., could only be used as a food source by the Rotifers if the flagella were removed from its lorica.

In May, Dinobryon divergens populations reached to its highest peak and Sphaerocystis schroeteri, a green algae with thick cell wall and embedded in a gelatinous sheath started to increase. This peak of Dinobryon sp., was associated with highest populations of adult E. gracilis and Ceriodaphnia reticulata.

In June and July, phytoplankton biomass increased rapidly due to the rapid growth of Sphaerocystis schroeteri along with the peaks of Oocystis spp., Cryptomonas spp., and high populations of Dinobryon sp. During this period of highest phytoplankton production, zooplankton populations increased slightly in 1984 but in 1985, it increased to the highest level. This increase was due to the rapid increase of two species of Rotifera, Kellicottia longispina and Trichocerca similis. However, K. longispina dominated the zooplankton populations. Both adult and nauplius of Eudiaptomus gracilis and Ceriodaphnia reticulata also reached to a second peak with the increased phytoplankton production. Sphaerocystis schroeteri is particularly unsuitable for the food of zooplankton because both thick cell wall and the gelatinous sheath decrease the

digestibility (Pourriot, 1957 and Saunders, 1969) and increase the possibility of viable gut passage (Porter, 1975). Porter (1976) observed that more than 90% of the undigested cells of Sphaerocystis sp., viable after gut passage. The rapid increase of the species at a time of heavy grazing could be due to a lack of competition from other algae through zooplankton grazing. Porter (1973) reported that gut passage could be very useful in fragmenting the colonies of Sphaerocystis sp., and increase the surface area to the volume ratio which permits more efficient utilization of the nutrients. It can also absorb the nutrients from other broken algal cells in the gut. The gelatinous sheath of the species also acts as a sieve which allows ionic nutrients to enter but prevents the digestive enzymes from entering in to the colonies.

Hutchinson (1967) reported that planktonic Rotifera in general feed either by sedimenting fine particles as a result of beating the coronal cilia or they are raptorial. Kellicottia sp., and Keratella sp., can use the mastrax to catch the flagellum of Cryptomonas sp., which then disintigrates, and the particulate matter liberated is eaten by them. Although the maximum populations of K. longispina and a small peak of K. quadrata coincided the phytoplankton peak, their succession may not be directly related because of their general inability to consume other phytoplankton

and limitations due to particle size.

After the decline of Sphaerocystis sp., green flagellates again flourished in August and September. Dinobryon divergens and Botryococcus braunii also reached to their peaks during this period in 1984 and in 1985, Cryptomonas sp., again increased slightly. Rotifera again dominated the zooplankton populations. Polyarthra vulgaris and Trichocerca similis reached to their maximum numbers but T. similis dominated the whole population. The adult and nauplii of E. gracilis and C. reticulata (in 1985 only) also reached to their late summer peak during this period.

Although the particle size is very important in determining the food of Rotifera, P. vulgaris is exceptional. Hutchinson (1967) reported that P. vulgaris eats mainly Cryptomonas sp., which may be as much as 50u long. This species may have much finer adjustment to specific food sizes moreover there is clear experimental evidence that certain foods are more easily and readily taken than others. The shape of the algal cells as well as their size, is evidently involved but chemical stimuli probably also play a part.

Eudiaptomus gracilis can grow and breed throughout the year because of their wide range of temperature tolerance

and the ability to consume a wide variety of food. Hutchinson (1967) reported that E. gracilis living in a pond consumed mainly desmids, when living with Actodiaptomus laticeps, it took mainly small green algae and when compared with Daphnia longiceps, the species was far less effective in the filtration of bacteria and when all else was excluded, it was able to live on minute detritus particles.

During October and November, phytoplankton populations declined to very low level with declining light and water temperature. The zooplankton populations were at highest level in 1984 and 1985 the numbers were quite high. The highest populations in 1984 was due to rapid increase of P. vulgaris and K. longispina. High populations in 1985 was also due to the Rotifers.

Klarer (1978) also reported high populations of Rotifera during late September and early October at a time when phytoplankton population was very low. Hutchinson (1967) reported that P. vulgaris, a perennial species, usually has a late spring or early summer maximum in a temperature range about 20°C but with the possibility of an autumnal maximum between 5 and 10°C. In the present study, P. vulgaris showed a single autumn peak during September and October when the water temperature ranged from 11 to 16°C.

However, Carlin (1943) suggested that factors other than temperature are involved.

In late November to December, phytoplankton populations were at the lowest level but the zooplankton populations were comparatively higher which was also due to the growth of Rotifers in favourable environmental condition.

CHAPTER — 6.

SESTON

6.1. Introduction :

All particulate organogenic material, living or dead, passively drifting in water was originally named as plankton by Hensen, 1887 (in Hutchinson, 1967). Later workers refined this concept, separated living and non living parts, identified different components of such an assemblage and named particular components separately. Kolkwitz, 1912 (in Hutchinson, 1967) introduced the term seston to include all particulate material present in the free water. This separation is arbitrary and not often completely followed and the precise definition of seston is still debatable.

In the present study, all suspended particulate matter which was caught in the seston trap (described in the methods and materials section) is considered as seston. This include organic detritus, living organisms and inorganic particles. The living organisms have been discussed in greater detail in the phytoplankton and zooplankton chapters. Organic detritus which were caught in the trap will be dealt with in this chapter. Organic detritus include dead organic matter from plants and animals

of both autochonous and allochthonous origin. This include faeces and other excreta of living organisms together with the associated microorganisms.

Although there are disagreements with the definition of seston, the functional concept is very clear. There are two main pathways of energy flow in the ecosystems : the grazing pathway in which the plant material is ingested directly by heterotrophic macroorganisms while they are green and living and the detritus pathway in which plant material dies and is decomposed by microorganisms before being available for macrorganisms.

At higher trophic levels energy is transferred from prey to predator but there is also a great energy transfer to the macroorganisms in the form of faeces, and dead animal material. During this process some of the organic material is dissolved in water, but this fraction is not included in the present study.

Although on an average less than 10% of the primary production is removed by grazing (Mann, 1972), in the past more emphasis has been placed on the grazing food chain to illustrate ecological energy transfer, and the detrital food chain have long been neglected in lacustrine ecosystem. The importance of detritus in the structure and function of

aquatic ecosystems is receiving more attention in recent years.

The most important component of seston is particulate organic detritus. Organic detritus was originally described by Odum and de la Cruz (1963) as dead particulate organic matter inhabited by decomposer microorganisms and the importance of detritus has since become the subject of a large and widespread literature.

Balogh (1958) has demonstrated that detritus, as egested material, is an important fraction of community metabolism. He suggested that significant "recuperative" food chains depend upon this source of detritus at each trophic level. Odum (1962 and 1963) emphasized that detritus originating as ungrazed primary production supports a "detritus food chain" which is essentially parallel to the conventional "grazer food chain" at succeeding trophic levels.

The sources and constituents of lacustrine detritus are diverse and poorly understood (Wetzel et al., 1972). The diversity of lacustrine detritus reflects the compound nature of most lake ecosystems. The role of allochthonous detritus in the metabolism and trophy of lakes has been

emphasized by Minshall, (1966); Moss (1970) and Hart & Howmiller (1975).

The significance of seston as potential sources of food of different kinds of aquatic animals have been well documented (Berrie, 1972; Mann, 1982 and Wotton, 1982).

A complete representation of the production of seston is, therefore, a pre-requisite of any treatment of lacustrine ecosystem structure and function.

The major goal of the presnt study is to determine the amount of primary energy flowing through seston to the sediment. In addition, seston biomass, composition and some aspects of chemistry were also considered.

6.2. Materials and Methods :

6.2.1. General :

The design of a trap is crucial in catching seston quantitatively. Pennington (1974) and Kirchner (1975) critically evaluated various types of seston traps used in the past. They concluded that vertically sided cylinders with unrestricted mouth opening gave an accurate approximation to the annual rate of sedimentation. Hargrave

and Burns (1979) suggested that the most efficient traps had a height to diameter ratio of greater than 5 which resulted in the formation of a turbulent free boundary layer at the bottom of the seston tubes.

In the present study, seston samples were collected using locally designed seston traps. Each trap consists of 4 one litre capacity measuring cylinders fitted in a metal frame. Each cylinder is 40cm high, 28cm^2 unrestricted mouth opening with a height to diameter ratio of 6.8. Two sets of traps were hung at station 1, one about 1m below the surface which would receive seston averaged over the circulation of water in the epilimnion during summer and the other approximately 1m above the bottom of the lake which would reflect the effect of deoxgenation on seston during the summer stagnation period. The upper trap was placed in high phytoplankton production zone and intended to collect seston material before being highly decomposed, much of which may not join the sediment. The bottom trap was placed just above the sediment and intended to collect all particulate material which may join the sediment. Seston traps were placed at station 1 only, a site judged to be representative of the whole lake. A float and an anchor were always used to maintain the upright position of the cylinders and prevent drifting. The contents of each cylinder were collected in a polythene bottle once a month

*Seston traps consists of 4 identical tubes and the materials collected in 1 tube was used in biomass determination. Seston collected in the other tubes could not be dried due to the nature of the analyses involved. However, it would have been useful to examine the variations among the identical tubes at least on some occassions.

throughout the second year of sampling and the cylinders were replaced immediately for the collection of the next sample. From each depth, one sample was considered for seston biomass and mineral content estimation, one sample for chemical analysis, one for microscopic examination and one for energy content. *see opposite.

6.2.2. Seston biomass :

The contents of one cylinder were filtered through a preheated (110°C for 3 hours) and weighed GF/A filter paper to minimize error due to moisture content. The sample with the filter paper was then dried in an oven for 6 hours at 110°C to get a constant dry weight. The weight of the filter paper was then subtracted and the biomass presented as dry weight of seston/m^2 lake surface/month. To minimize the loss of volatile organic matter, the drying temperature could not be increased although it may slightly over estimate the seston biomass due to water molecules tightly bound with the seston material (Allen et al., 1974).

6.2.3. Seston composition :

The contents of one cylinder was concentrated to 25ml by sedimentation for the microscopic examination of different components of seston. The concentrated sample was

then transferred to a labelled vial and kept in a refrigerator before being examined. They were generally examined within a week of collection. Having looked at few samples preliminarily under a high power compound microscope, different components of seston were categorized as organic detritus, diatoms, other algae, recognizeable plant parts, Chironomids, zooplankton and mineral matter. Different catagories of seston were then evaluated by the percentage frequency of occurrence method. From 25ml of the concentrated sample, two drops of seston were placed on a microscopic slide, covered with a coverslip and then 10 microscopic fields from each slide were examined. To avoid bias, a crossed hair was always used in an eyepiece. All component of the different categories of seston which came under the cross in each microscopic field was counted. A total of 40 slides, totalling 400 microscopic fields of observations were used in calculating the percentage composition of different categories of seston.

6.2.4. Organic and mineral matter (loss on ignition) :

Organic matter dominates the composition of seston but it is extremely difficult to investigate because there is no known way by which the total quantity of the organic matter can be estimated with the degree of accuracy usual in routine quantitative inorganic analysis (Hutchinson, 1967).

The simplest and most widely used method of organic content estimation is the "loss on ignition". Hutchinson (1957) and Allen et al., (1974) critically reviewed the method and pointed out the possibilities of over estimating the organic content due to additional loss of tightly bound water.

However in the present study the organic matter and mineral content of the seston were determined following the method of "loss on ignition". The same seston sample which was used for biomass estimation was ashed in a muffle furnace at 600°C for 12 hours in a dried porcelain crucible. The ash weight of the seston was determined using a correction factor (0.001g) for the weight loss of filter paper at 600°C. The percentage loss on ignition was calculated as :

$$\frac{\text{Dry wt. of seston (110°C)} - \text{Ash wt. of seston (600°C)}}{\text{Dry wt. of seston (110°C)}} \times 100$$

The ash remaining after the loss of organic matter on ignition was considered to be the mineral content of seston.

6.2.5. Carbon estimation (Loss on ignition) :

Carbon estimation from loss on ignition of organic

matter is a very popular and widely used technique due to its simplicity. Many workers consider that the method is too rough. Ball (1964) examined the relationship between organic matter and carbon using the loss on ignition method and other similar methods and found an acceptable correlation. He also claimed that the results are less variable than other similar methods. The figure for the ratio of organic matter/organic carbon which has long been accepted is 1.72 and is based on the assumption that the organic matter contains 58% carbon (Allen et al. 1974). However, the results obtained by this method is to be considered as approximate only. In the present study, carbon content of seston was calculated as :

$$\text{Carbon} = \frac{\text{Sestonic organic matter (Loss on ignition)}}{1.72}$$

and all the results were converted as mg C/g of seston.

6.2.6. Chemical analysis :

6.2.6.1. General :

Seston samples were filtered, dried (110°C) and carefully weighed as per biomass determination. Known

quantities of the samples were placed in a micro-Kjeldahl digestion flask and then 10ml of the digestion mixture was added to each flask. The digestion mixture was made with 0.6g Selenium dioxide, 170 ml nitrogen free concentrated H2SO4 and made up to 500ml with distill water. The samples were then boiled until the liquid became clear and colourless, normally for about 10 hours to digest all the organic matter in the seston. After cooling the samples in room temperature, 50ml distilled water was cautiously added in each flask and the contents were transferred to a 250 ml capacity conical flask. The digested samples were filtered with GF/A filter papers and the filtrate were neutralized by titrating with 40% NaOH using a litmus paper as indicator and the samples were made up to 250ml.

6.2.6.2. Total nitrogen :

It was assumed that all the nitrogenous compounds were converted into ammonia during the micro-Kjeldahl process. From 250ml of the digested seston sample, a subsample of 10ml was taken in a 100ml conical flask and diluted to 50ml. The ammonia concentration of the diluted sample was determined spectrophotometrically according to Zadorojny et al.,(1973). All the results were multiplied by 5 as dilution factor and expressed as mg NH4-N/g of seston.

*Nitrogen and Phosphorus : During acid digestion of seston and sediment in micro-Kjeldahl process, digestion time was determined by plotting the concentrations against hours of digestion and it was found that 10 hours were enough to digest all organic matter. For accurate estimation of Nitrogen & Phosphorus concentrations, they were diluted using subsamples. Some variation is expected due to dilution

6.2.6.3. Total soluble reactive orthophoshate :

The total soluble reactive orthophosphate was determined using the remaining digested seston sample. A subsample of 5ml was separated and diluted 40 times and the phosphate concentration was measured spectrophotometrically according to Mackereth et al., (1978). All the results were multiplied by 40 as dilution factor and expressed as mg PO4 - P/g of seston. *see opposite.

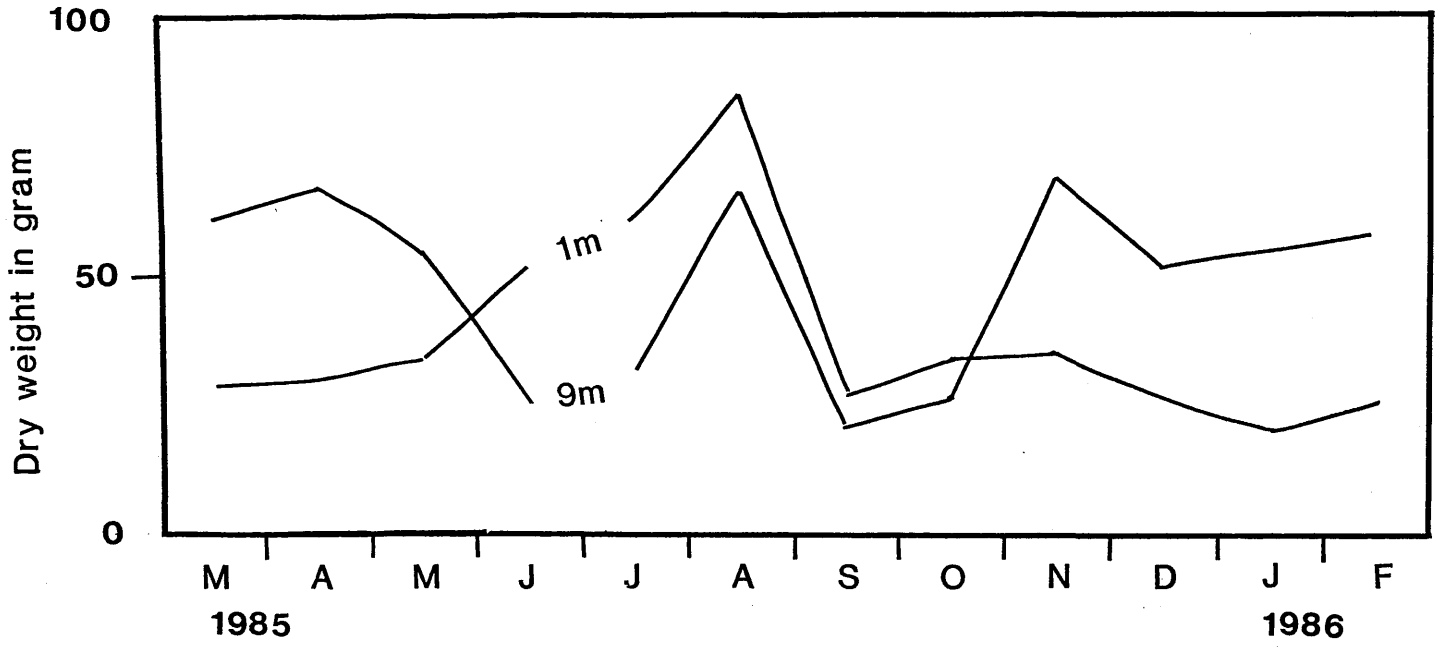
6.2.7. Energy content :

Seston samples were sedimented in a 1 litre capacity cylinder for about 3 hours. The supernatant was siphoned carefully with a thin plastic tube, each sample was transferred to a desiccator and dried in an oven at 110°C for about 4 hours. Each sample was ground in a small mortar and kept in labelled vial until the analyses were made.

The energy content of the seston were determined with a microbomb Calorimeter (Model AH 12 EF 2). The pellets made from the whole seston sample did not burn completely in the bomb Calorimeter because of the low calorific value. To facilitate burning the seston, they were mixed with Benzoic acid, a highly combustable material with known calorific value. Preliminary trials determined that complete

Figure 44. Seasonal variations of seston biomass from March, 1985 to February, 1986. Seston biomass is expressed in g/m^2 lake surface/month.

Seston biomass



combustion occurred in pellets with a 1:4 ratio of seston : Benzoic acid. The two components were carefully ground and mixed together before being made into pellets. There was a good agreement between duplicate results for all samples (see chapter - 7. Sediment, for discussion of the method used).

Finally, the energy content of the seston was calculated by subtracting the energy content of the Benzoic acid from the total energy content of the pellet and was expressed as Kilo Joules/g dry weight of seston.

6.3. Results and Discussion :

6.3.1. Seston biomass :

Seston biomass showed a distinct seasonal variation in Dubh Lochan. Apart from the single summer peak at 9m depth, the seston biomass at 1m and 9m depth showed almost mirror images (Fig. 44).

In the upper trap, seston biomass varied from 20 to 85g/m^2 lake/month. At the beginning of the study period in March, 1985, seston biomass was about 28g/m^2 lake/month, it increased gradually to 34g/m^2 lake/month in May and then a rapid increase from late May lead to its single peak in

August to about 85g/m^2 lake/month. It declined sharply in september to approximately 27g/m^2 lake/month and after the autumn overturn, it increased slightly in October and November and reached to its lowest level in January, 1986 to about 20g/m^2 lake/month. In the lower trap (9m depth), the seasonal pattern was quite different from the upper trap. At the beginning of the study in March, 1985, seston biomass was approximately twice as high as in the upper trap. A gradual increase from March lead to its first peak in April to about 67g/m^2 lake/month. After this peak, seston biomass declined sharply to 25g/m^2 lake/month in June, increased slightly in July and then a rapid rise lead to its second peak in August. This peak was similar to the first peak in size. It declined rapidly in September to about 21g/m^2 lake/month, increased slightly in October and then a rapid rise lead to its third and highest peak to about 69g/m^2 lake/month in November and December and slightly higher levels remained throughout the winter.

High seston biomass in June and July in the upper trap was contributed by a massive growth of Protoderma viride inside the seston tubes at a time of the highest production of both phytoplankton (Fig. 23) and zooplankton (Fig. 36). During this period Sphaerocystis schroeteri (Fig. 24), Cryptomonas spp., (Fig. 28), and Oocystis spp., (Fig. 26) among phytoplankton and Kellicottia longispina (Fig. 40),

Ceriodaphnia reticulata (Fig. 39), Trichocerca similis (Fig. 42) and Eudiaptomus gracilis (Fig. 37), among zooplankton reached to their peaks throughout the water column. Although both phytoplankton and zooplankton production was low during the highest production of seston in August, it was probably due to the time taken in sedimentation of plankton produced earlier in June and July. During this period, massive growth of diatoms were also observed (Fig. 45) in the seston trap. The significant contribution of phytoplankton in the production of seston has been well documented (Moss, 1970; Reed, 1970; Lundgren, 1978; and Polunin, 1982), although it is extremely variable from lake to lake depending on the productivity. The slight increase of seston biomass during October and November could be contributed by increased supply of allochthonous organic matter (Fig. 46).

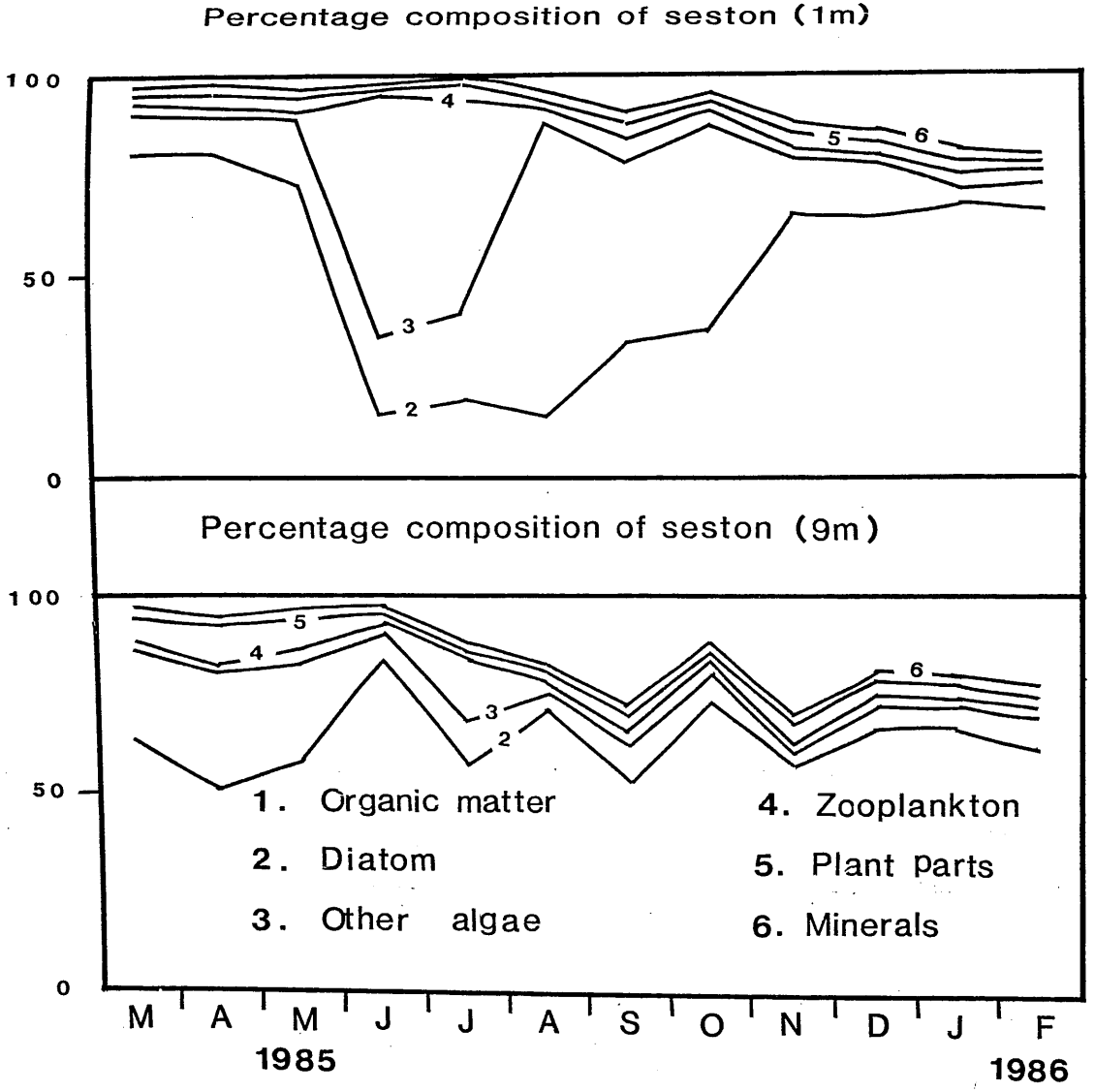
High seston biomass in the lower trap (9m depth) during the spring was probably due to autochthonous organic detritus produced by the death and decomposition of the littoral macrophytes in the previous winter and took a long time to settle from the surface to the bottom of the lake. With increased phytoplankton production, seston biomass decreased sharply from May and was low throughout the summer except in August which could also be related with the slow rate of sinking of phytoplankton after their death.

Hutchinson (1967) reported that phytoplankton on an average take 3 to 4 months to settle at the bottom although it varies from species to species and Lake to Lake according to the depth. After sedimenting the high phytoplankton population produced in summer and resuspension of the sediment after the overturn, an autumn peak of seston biomass is common (Leach, 1975; Hallegraeff, 1978 and Pradeep & Gupta, 1986). High seston biomass during the winter months is probably due to both autochthonous and allochthonous organic detritus. The autochthonous sources include the death and decomposition of huge quantities of littoral macrophytes and aquatic mosses. The littoral macrophytes in Dubh Lochan is dominated by Phragmites sp., which is followed in order of importance by Nymphaea sp., and Nuphar sp., and aquatic mosses are dominated by Sphagnum sp.

Maximum input of rainwater through the inflow during the winter months also contributed high quantities of organic matter and inorganic materials. The sources of this allochthonous organic matter include the vegetation of the catchment particularly the soft wood and humic substances from the peat layers of the moorland in the upper reaches of the catchment of Dubh Lochan.

Allochthonous organic matter could contribute

Figure 45. Seasonal variations of seston composition from March, 1985 to February, 1986. Seston composition is expressed as percentage.


Percentage composition of seston (1m)
100
50
0
4
5
6
3
2
Percentage composition of seston (9m)
100
50
0
5
4
6
3
2
1. Organic matter
2. Diatom
3. Other algae
4. Zooplankton
5. Plant parts
6. Minerals
M A M J J A S O N D J F
1985
1986

significantly to the seston biomass in lakes (Minshall, 1966; Leach, 1975) although it is extremely variable from lake to lake depending on the geographical condition, feeder streams and the nature of the neighbouring area.

6.3.2. Seston composition :

The components of seston were categorized into 6 groups viz: organic detritus; diatoms; other algae; recognizeable plant parts; zooplankton including Chironomidae and minerals. Great variations in the composition of seston was observed both seasonally and vertically (Fig. 45).

Organic detritus :

Organic detritus constituted the major bulk of seston and showed great differences between the upper and lower traps.

In the upper trap (1m depth), organic detritus varied from 16-80% of total seston. During March and April, 1985, organic detritus was at its highest level and contributed 80% of seston. It declined slightly in May and then a rapid decrease resulted in its lowest level to approximately 16% in June and similar levels remained up to August. Organic detritus increased gradually from August and reached to 65%

in November and slightly higher levels remained throughout the winter.

In the bottom trap (9m depth), organic detritus ranged from 50% to 84% of the total seston. Detritus constituted 63% in March, 1985, it declined to the lowest level in April to approximately 50% and then increased gradually to the highest level in June, comprising 84% of the seston. After this peak, it declined to 58% in July. From July to February, 1986, detritus contributed 58-73% of seston showing irregular fluctuations.

Although, the rate of decomposition of organic matter must be expected to be higher during the warmer summer months, low concentrations of detritus in the upper trap from June to October was due to the influence of algal growth inside the seston tubes. Highest composition of organic detritus in the bottom trap in June and high concentrations during the whole summer could be related to the high rate of decomposition due to microbial activity (Jones, 1976).

Diatoms :

Diatoms constituted the second important component of

biosestón at both depths and showed distinct seasonal and vertical variations.

In the upper trap, diatoms constituted between 5 and 71% of the total seston. During high production of diatoms throughout the water column in spring they contributed between 9 and 16% of seston . The population increased gradually from June and reached to 71% in August. In September and October, diatoms declined to 50%. In November, the Diatoms declined very sharply to 15% and a gradual decrease from December resulted in their lowest level in January, 1986.

In the lower trap, the contribution of diatoms were much lower than the upper trap and varied between 3 and 30% of total seston. Diatoms constituted 23% of seston in March and then increased to the highest level of about 30% in April. They declined sharply in May and reached to 6% in June. The contribution of diatoms from June to February, 1986 was very low, ranging from 3 to 10% with irregular fluctuations.

Other algae :

All other algal species constituted the third important component of biosestón.

In the upper trap, all other algal species together contributed between 2 and 59% of total seston. From March to May, 1985 they were very low, contributing between 2 and 3%. The populations increased very rapidly to 59% in June, decreased slightly in July and then declined very rapidly to 4% in August. From August to February, 1986, the contribution of other algal species were very low, ranging from 2-6% of the seston.

In the lower trap, all other algal species contributed between 2 and 3% of the seston throughout the year except in July when they reached to approximately 16%.

Very high contribution of other algal species in June and July in the upper trap and slight increase in July in the lower trap was mainly due to the growth of a periphytic green algae, Protoderma viride (not observed in plankton) inside the seston tubes rather than the sedimentation. Although several species of algae showed summer maximum throughout the water column, they could not be recognized in the seston because after their death and decomposition, they joined detritus.

Recognizable plant parts (mainly partly decomposed aquatic macrophytes and moss leaves) :

Recognizable plant parts were always very low in both the upper and lower traps.

In the upper trap, it varied from 2-4% of the seston and showed no distinct seasonal distribution patterns.

In the bottom trap, it contributed between 2 and 9% of the seston with the highest level in April which could be related with the death and decomposition of littoral macrophytes during the previous winter. Plant parts originating from allochthonous sources and drifted into the Lake could also be an important source. It is extremely difficult to measure the relative proportions of allochthonous and autochthonous plant parts into the composition of seston and no such attempt was made in the present study.

Zooplankton :

The contribution of zooplankton in the seston in both the upper and lower trap was very low, ranging from 2 to 3% and showed no distinct seasonal or vertical distribution

patterns. The rate of decomposition of zooplankton is higher than the other components of biosestón and after their death, they soon become unrecognizable detritus.

Minerals :

Mineral content of seston showed similar seasonal patterns in both the upper and lower trap but the percentage of minerals were slightly higher in the lower trap than the upper trap.

In the upper trap, it varied from 1-21% of total seston. From March to August, 1985, mineral composition varied between 1 and 5%. It increased to 10% in September and then declined to 5% in October followed by a gradual increase to the highest level of approximately 21% in February, 1986.

In the lower trap, mineral composition of seston ranged from 3 to 30% of total seston. Mineral contents of seston were very low from March to June, 1985 and varied between 3 and 6%. It increased gradually from July and reached to 28% in September. In October, it declined to 11% and again increased to the highest level of approximately 30% in November. The concentrations declined to 20% in December and similar levels remained throughout the winter.

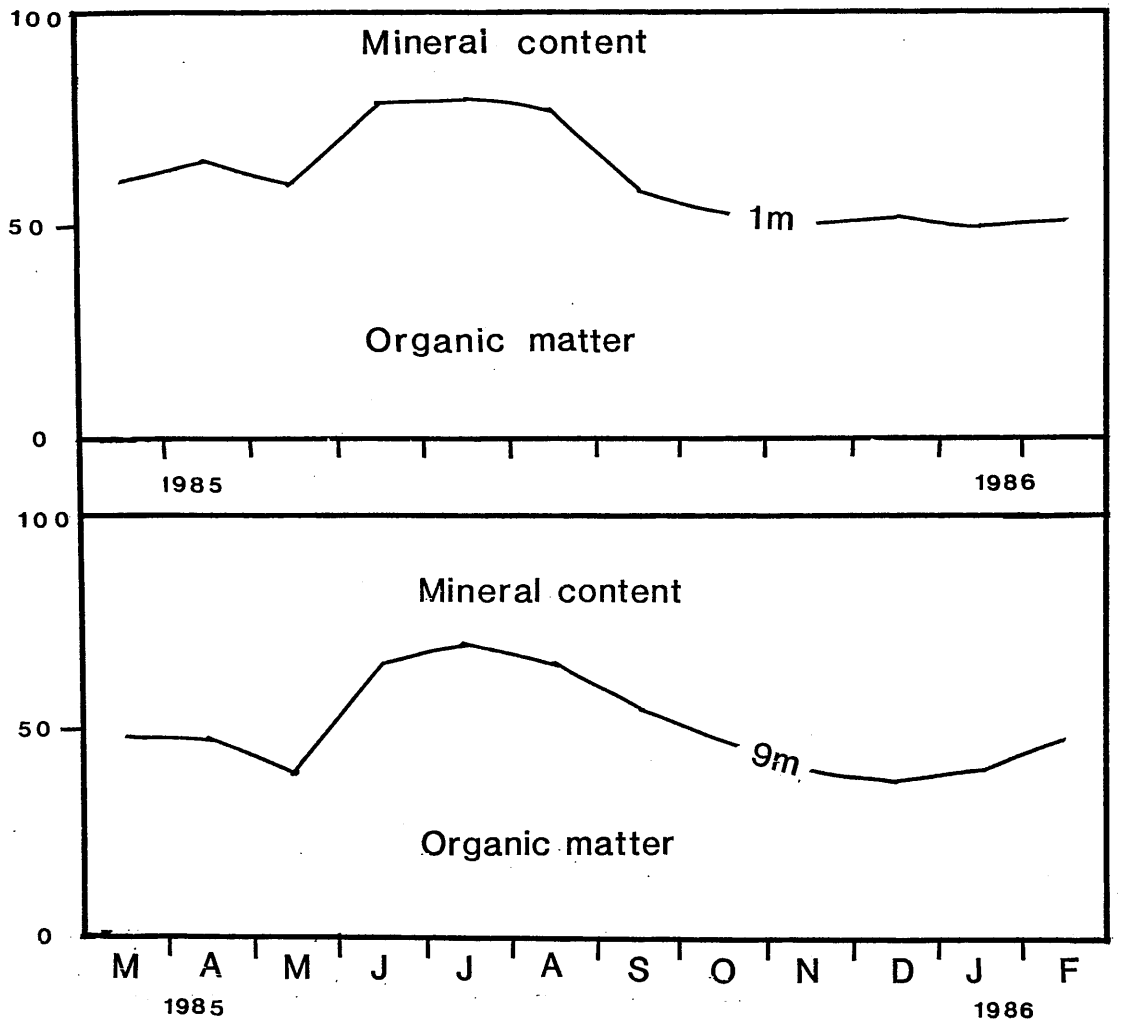
The mineral content of seston showed a close relationship with rainfall (Table 1). Highest compositions of minerals in November and comparatively high levels during the whole winter seems to be related with the maximum inflow of rainwater carrying fine mineral particles from the neighbouring area i.e. allochthonous rather than recycling from the sediment at times of turnover.

The mineral content estimated after the loss of organic matter on ignition was much higher than the present method and varied between 35 and 65% of total seston (Fig. 46). However since loss on ignition was done on dried samples (at 110°C for 3 hours), and if organic matter contains approximately 90% water then 35% mineral is equivalent to 5.1% of a hydrated sample and similarly 65% is equivalent to 15%. Most minerals are denser than organic detritus and algal material. The frequency of occurrence of detritus and algal material were, therefore, higher than mineral particles. Although the composition of minerals in seston assessed by the two methods varied greatly, the seasonal fluctuations showed similar patterns during the whole period of study.

The results of seston composition indicate that the upper trap (1m depth) was not suitable for seston collection

Figure 46. Seasonal variations of organic matter and mineral content in seston from March, 1985 to February, 1986. Organic matter and mineral content is expressed as percentage.

Organic matter and mineral content of seston



because of periphytic algal growth inside the seston tubes during the summer months. The bottom trap was free from such alagal growth and a true picture of seston at that depth was observed.

6.3.3. Organic and mineral matter (loss on ignition) :

Total organic content of the seston was always higher in the upper trap than the bottom trap (Fig. 46).

In the upper trap, organic matter ranged from 50 to 80% of total seston. From March to May, 1985 it varied between 60 and 65%. The concentrations increased sharply to 79% in June and similar levels remained till August. It declined sharply to 58% in September and 53% in October and similar levels remained up to February, 1986.

In the bottom trap, organic content varied between 35 and 69% of total seston. Organic matter contributed 48% of seston in March, 1985, it declined gradually to 39% in May and then a rapid increase in June lead to the highest level of about 69% in July. The concentrations declined gradually from August and reached to 37% in December, it increased slightly in January, 1986 and reached to 48% in February.

Organic content of the seston in the upper trap was

always higher than the bottom trap which could be related to the degree of decomposition. High quantities of seston produced in the upper few metres of water takes a long time to reach the bottom and during the sinking process, seston particles are decomposed into fine detritus due to microbial activity.

High percentage of organic matter in the upper trap from June to August was contributed mainly by the growth of Protoderma viride inside the seston tube rather than the true sedimented seston. The bottom trap was free from such influence, high concentrations of organic matter could be related with the nature of detritus, produced mainly from the death and decomposition of phytoplankton. Although seston biomass was high during the winter months (Fig. 44), the percentage loss on ignition was low. During this time most of the seston originated from littoral macrophytes and allochthonous organic and inorganic matters of very different nature.

Mineral content of seston in the bottom trap was always higher than in the upper trap (Fig. 46). In the upper trap, mineral content of seston ranged from 20-50%. From March to May, 1985, it varied between 35 and 40% of total seston. The concentrations declined sharply to 21% in June and similar levels remained till August. It increased sharply

in September and then a gradual increase lead to the highest level of about 50% in November and similar levels remained up to February, 1986.

In the bottom trap, mineral contents were much higher than the upper trap and varied between 31 and 63% of seston. The concentrations increased gradually from 52% in March to 61% in May. It declined sharply in June and reached to the lowest level of approximately 31% in July. The concentrations increased gradually from August and reached to the highest level of about 63% in December and then declined gradually to 52% in February, 1986.

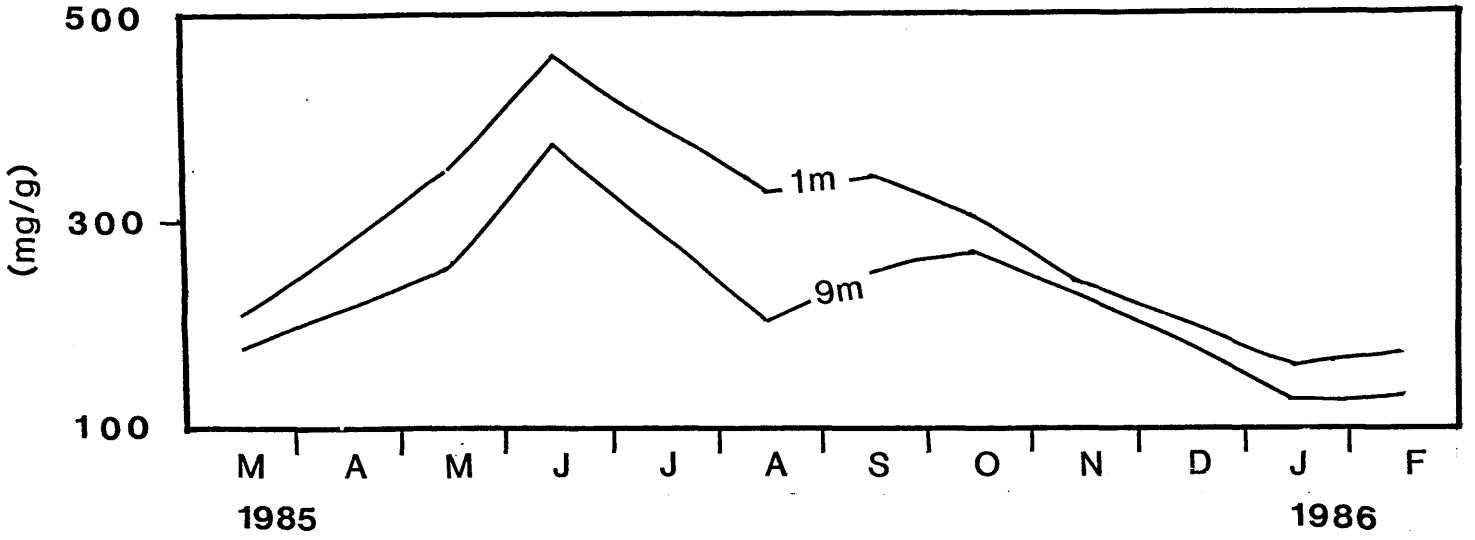
Mineral particles of seston coming mainly from allochthonous sources showed a direct relationship with rainfall (Table 1) and inflow rates. Lowest concentration during the dry period in summer was associated with low inflow rate due to low rainfall and high concentrations duing the whole winter could be related with high inflow rate due to maximum rainfall, carrying maximum amount of mineral particles into the lake.

6.3.4. Carbon content (Loss on ignition) :

Carbon content of seston showed similar patterns of seasonal variations although the values were always higher

Figure 47. Seasonal variations of carbon content in seston from March, 1985 to February, 1986. Carbon content is expressed in mgC/g of seston.

Carbon content of seston



in the upper trap than the lower trap (Fig. 47).

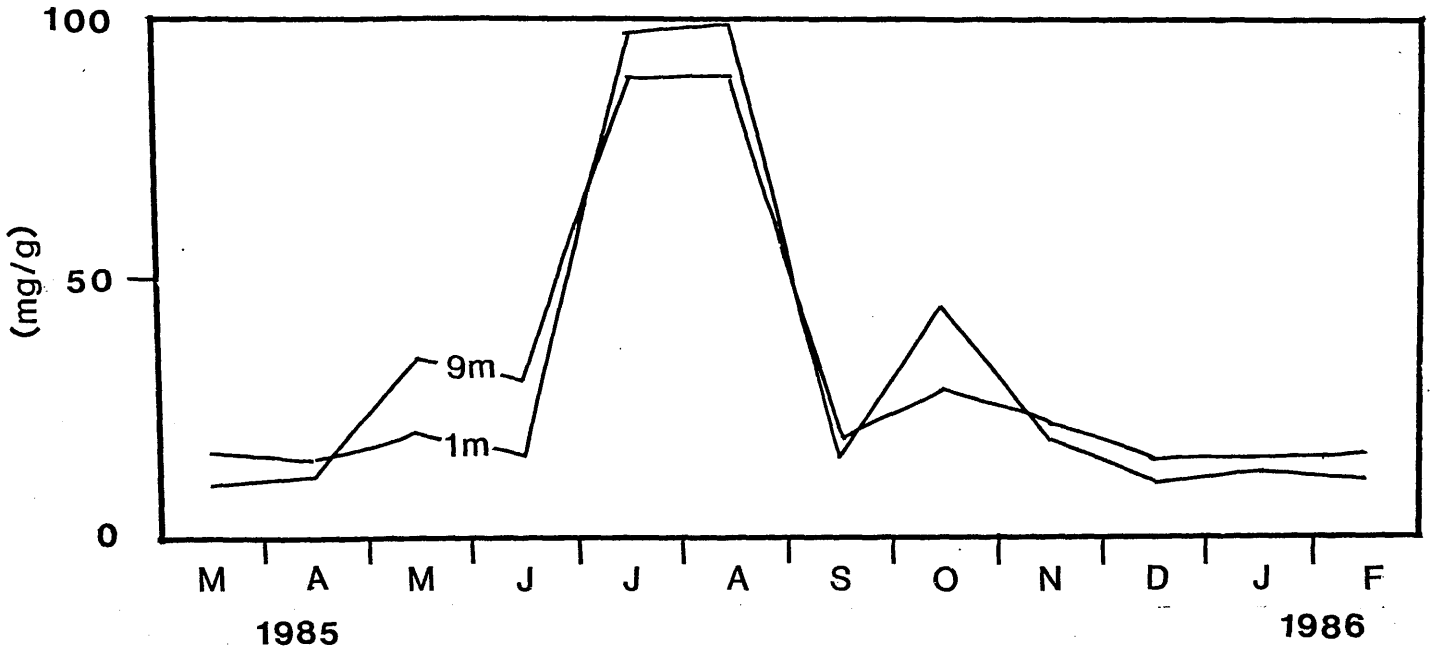
In the upper trap, carbon content varied betwen 160.4 and 460.4 mg/g. Carbon content was very low in March (211.3 mg/g), 1985, it increased gradually through July and reached to the highest level (460.4 mg/g) in June. It declined through July and reached to 327.6 mg/g in August and then increased slightly (342.7 mg/g) in September. Carbon content declined gradually from October and reached to the lowest level (160.4 mg/g) in January, 1986 and then increased slightly in February.

In the lower trap, carbon content ranged from 125.11 to 378.5 mg/g of seston. It showed similar patterns of seasonal variations as was observed in the upper trap.

The highest carbon content in the upper trap in June and high level throughout the summer months could be due to periphytic algal growth inside the seston tubes rather than sedimentation of seston. Gorham & Sanger (1967) reported that carbon content of phytoplankton is much higher than the organic detritus. The highest level of carbon in the upper trap in June and high level from late spring to mid summer could be due to high concentration of algal material in the seston. Low carbon content during early spring and the whole winter could be due to increased participation of

Figure 48. Seasonal variations of total nitrogen content in seston from March, 1985 to February, 1986. Nitrogen content is expressed in mg NH_4 - N/g of seston.

Total nitrogen concentration in seston



non-algal material in the seston which originated from both autochthonous (death and decomposition of aquatic macrophytes) and allochthonous sources.

6.3.5. Total nitrogen :

Total nitrogen concentrations of seston showed great seasonal variations in both the upper and lower traps (Fig. 48).

In the upper trap, nitrogen concentrations ranged from 11-99 mg/g of seston with two distinct seasonal peaks, one in the late summer and the other in early autumn. From March to June, 1985, the concentrations varied from 15 to 20 mg/g of seston. It increased very rapidly in July to 96mg/g and reached to the highest level of 99mg/g in August. After this peak the concentrations declined sharply in September to 15 mg/g and again increased to a second peak of approximately 45 mg/g of seston in October. Nitrogen concentrations declined sharply in November and reached to the lowest level of approximately 11mg/g in December and slightly higher levels remained throughout the winter.

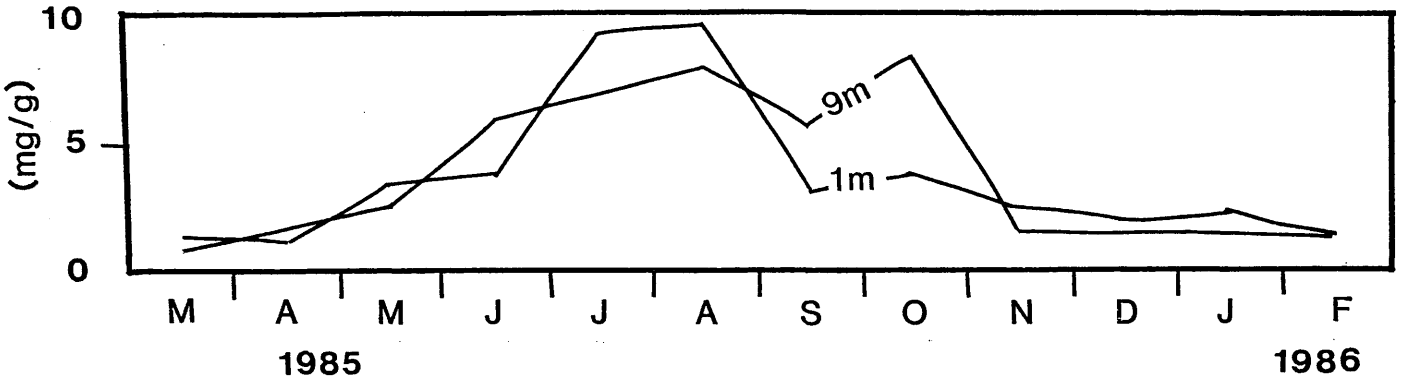
In the bottom trap, the concentrations varied from 10-89 mg/g of seston and showed three distinct seasonal peaks, a major peak in summer and two other minor peaks in

late spring and early autumn. The lowest concentration of nitrogen was observed in March, 1985, it increased slightly in April and then a rapid rise lead to the first peak of approximately 35mg/g of seston in May. It declined slightly in June and then a rapid increase lead to the highest peak of about 89mg/g of seston during July and August. After this peak, nitrogen concentrations declined sharply to 15 mg/g in September and again increased to its third peak of about 30mg/g in December and similar levels remained throughout the winter. The concentration of nitrogen depends upon the nature and composition of seston. The highest concentration of nitrogen during July and August in the upper trap was contributed by living algae due to the growth of Protoderma viride inside the seston tubes. Among nitrogenous compounds proteins are the most important constituents of living tissue and account for a large proportion of total nitrogen content (Allen et al., 1974). Barnes & Mann (1980) reported that some species of algae may contain up to 50% protein when they are growing actively.

Although the bottom trap was free from algal growth, the highest concentrations of nitrogen in the same period could be due to high concentrations of algal material in the seston after their death and decomposition. Hallegraeff (1978) reported that proteins are the major organic compounds in the seston samples ranging from 13.06 to 37.13%

Figure 49. Seasonal variations of total soluble reactive orthophosphate concentrations in seston from March, 1985 to February, 1986. Orthophosphate concentration is expressed in mg PO4 - P/g of seston.

Orthophosphate concentration in seston



of dry weight and a positive correlation was observed between phytoplankton biomass and the protein content of seston.

Two other minor peaks of total nitrogen in seston during late spring and early autumn coincides with highest level of diatoms in the composition of seston (Fig. 45).

Low concentrations of nitrogen during early spring and winter in both the traps could be related with increased concentrations of non-algal materials in the seston, originated from both autochthonous (death and decomposition of aquatic macrophytes) and allochthonous sources containing less protein. A similar observation was also made by Hallegraeff, (1978).

6.3.6. Total soluble reactive orthophosphate :

Total soluble reactive orthophosphate concentrations showed distinct seasonal variations in both the upper and lower traps (Fig. 49).

In the upper trap, orthophosphate concentrations varied between 1.2 and 9.7 mg/g of seston. The lowest concentration of orthophosphate was observed during March and April, 1985. It increased gradually from late April and

reached to 3.8 mg/g of seston in June. Orthophosphate concentration increased sharply to 9.2 mg/g in July and reached to the highest level of approximately 9.7 mg/g in August. It declined sharply to 3.2 mg/g in September and again increased to 3.8 mg/g of seston in October. The concentrations declined gradually to 2 mg/g in December and similar levels remained throughout the winter.

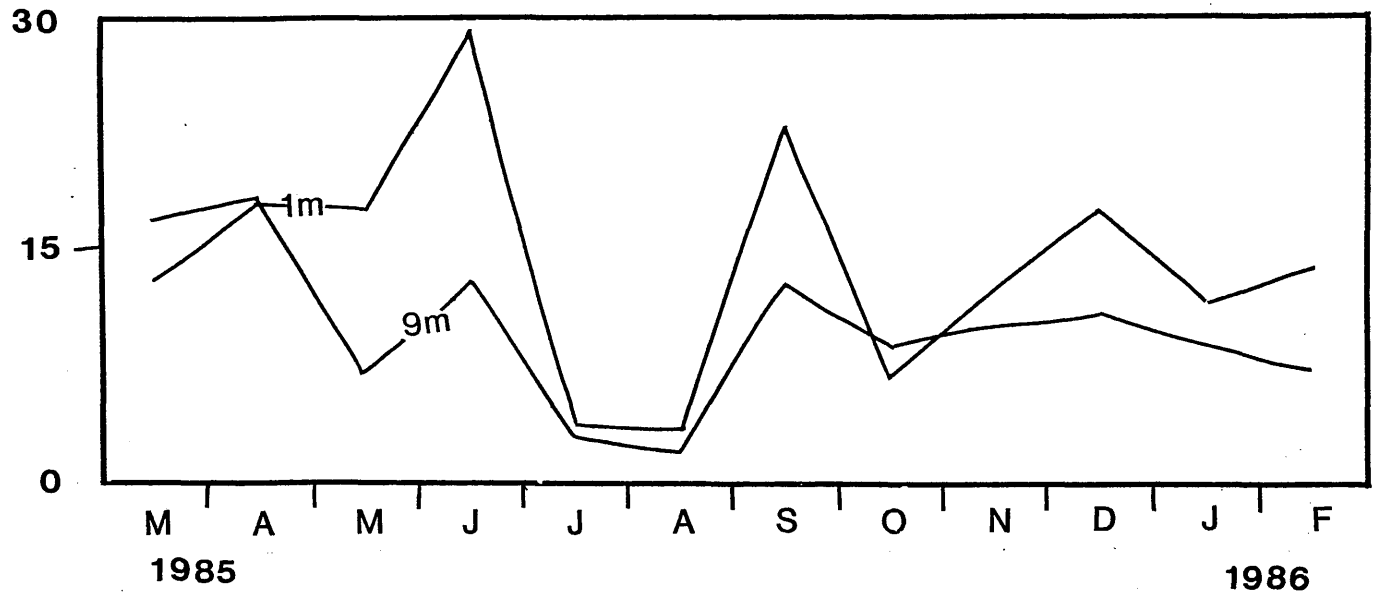
In the bottom trap, orthophosphate concentrations ranged from 0.8 to 8.4 mg/g of seston. The lowest concentration was observed in March, 1985. It increased gradually from April and reached to 2.5 mg/g in May. The concentrations increased sharply from late May and reached to its first peak of about 8 mg/g in August, it declined to 5.8 mg/g in September and again increased to the highest level of about 8.4 mg/g of seston in October. After this peak, the concentrations declined sharply to 1.6 mg/g in November and similar levels of orthophosphate remained throughout the rest of the period of study. Like total nitrogen, the highest concentration of orthophosphate in the upper trap during July and August was contributed by living algae due to the growth of Protoderma viride in the seston tube at a time when phytoplankton biomass throughout the water column was at the highest level. Two other small rises of orthophosphate concentrations during May and October could be due to high concentrations of algal

material in the seston. Sholkovitz & Copland (1982) reported that seston samples collected from the surface waters had high concentrations of phosphorus in spring and highest concentrations during the summer months with increasing phytoplankton biomass.

High concentrations of orthophosphate in the bottom trap from June to September and the highest level in October could be related with phosphorus adsorption by sedimenting seston (Gachter & Mares, 1985). Settling seston is composed of a variety of autochthonous and allochthonous organic and inorganic material colonized with bacteria and fungi. Therefore, it is extremely difficult to separate various possible mechanisms of orthophosphate adsorption. However, based on the observations reported in the literature, it is suggested that active uptake of orthophophate by sinking algae or by heterotrophic microorganisms colonizing the settling material may be important. Uptake of orthophosphate by aquatic bacteria has been reported by several workers (e.g. Barsdate et al., 1974; Planas, 1978; Fleisher, 1983). Levine & Schindler (1980) concluded that the fluxes of $PO4^{3-}$ to seston in the epilimnion and hypolimnion are comparable and the hypolimnetic decomposers rapidly and actively take up $PO4^{3-}$.

Figure 50. Seasonal variations of Carbon / Nitrogen ratio of seston from March, 1985 to February, 1986.

Carbon/Nitrogen ratio of seston



Very low concentrations of orthophosphate in both upper and lower trap in early spring and the whole winter, could be related with low concentrations of algal material in the seston. During this time the growth of phytoplankton was very low and the sources of detritus was mainly aquatic macrophytes and allochthonous organic matter.

6.3.7. Carbon/Nitrogen ratio :

Carbon/Nitrogen (C/N) ratio in seston varied greatly both seasonally and vertically (Fig. 50).

In the upper trap C/N ratio ranged from 3.29 to 28.9. The C/N ratio increased from 13.8 in March to 18.01 in April, declined slightly in May and again increased rapidly to its highest level (28.9) in June. It declined rapidly in July (4.01) and reached to the lowest level (3.29) in August. The C/N ratio increased sharply in September (22.9) and again declined rapidly in October (6.7), it increased through November and reached to 17.8 in December. It declined to 12.1 in January, 1986 and again increased slightly in February.

In the lower trap, C/N ratio varied from 2.3 to 18.09. The C/N ratio increased from 16.8 in March to the highest level (18.01) in April, declined sharply in May and again

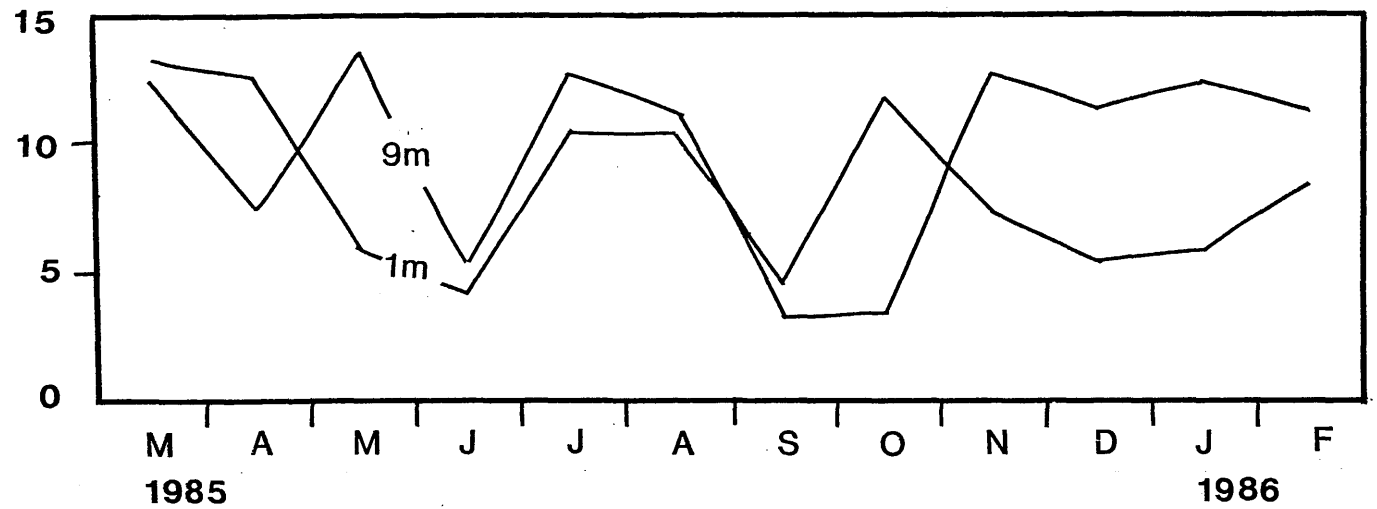
increased to 12.6 in June. It declined sharply in July and reached to the lowest level (2.3) in August. The C/N ratio increased sharply in September (13.2) and then declined slightly in October. It increased slightly in November and December (11.09) and again declined slightly in January, 1986 and February (7.53).

Carbon/Nitrogen ratio of most phytoplankton in the laboratory culture generally ranges from 5 to 10. The C/N ratio of particulate organic matter increases somewhat to values of 10 to 13 indicating a tendency for the nitrogen to be lossed at a faster rate than organic carbon (Holm - Hensen, 1972). Holm - Hensen reviewed the literature on C/N ratio and pointed out that there are many reports of C/N ratios ranging from 2 or 3 up to 30 and higher in natural condition depending on the nature of the material and the environmental condition. In the laboratory culture of marine phytoplankton, he observed C/N ratio ranging from 4 to 50 depending on the availability of fixed nitrogen in the cells.

In the present study, C/N ratio in the lower trap seems to be well within the normal range reported in the literature except two slightly higher values during March and April than the rest of the period.

Figure 51. Seasonal variations of Nitrogen / Phosphorus ratio of seston from March, 1985 to February, 1986.

Nitrogen/Phosphorus ratio of seston



6.3.8. Nitrogen/Phosphorus ratio :

Nitrogen/Phosphorus (N/P) ratio showed three distinct seasonal peaks in both the upper and lower trap (Fig. 51).

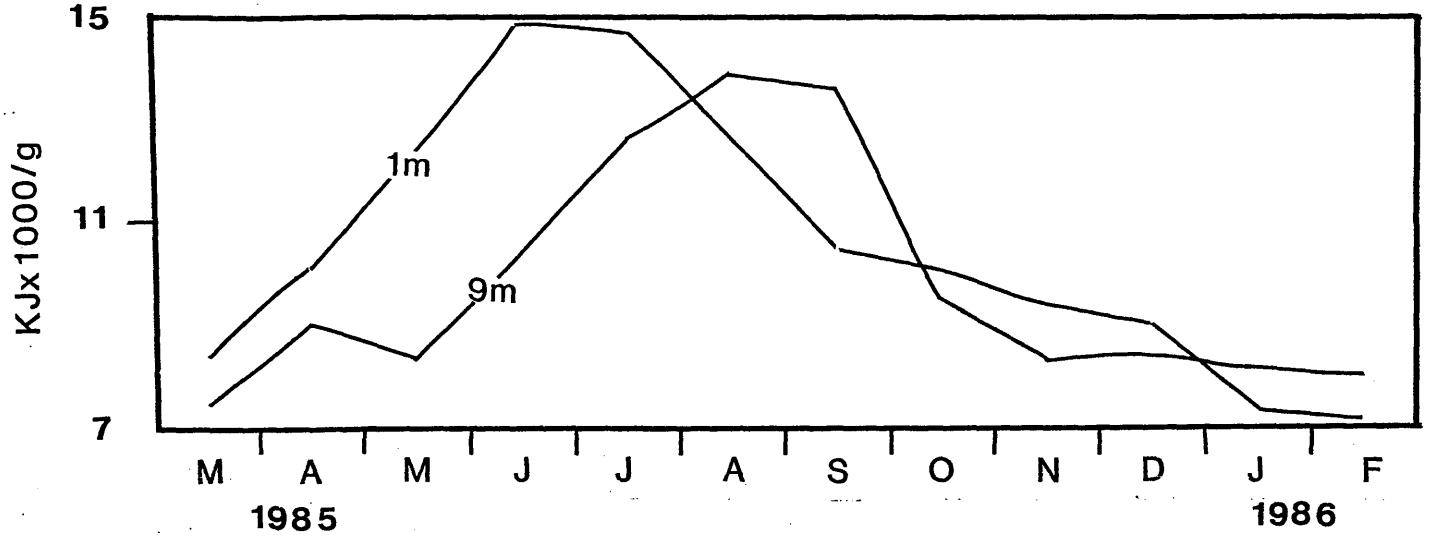
In the upper trap, N/P ratio varied between 4.2 and 13.3. The highest N/P ratio was observed in March, 1985, it declined slightly in April and a rapid decrease in May lead to the lowest level in June. The N/P ratio increased rapidly to approximately 10.5 in July and August and then declined sharply to 4.7 in September. It increased rapidly to 11.8 in October and then declined gradually to 5.5 in December and again increased slowly to 8.5 in February, 1986.

In the bottom trap, N/P ratio ranged from 3.3 to 13.5. In March, 1985, N/P ratio was very high (12.5), it declined sharply to 7.5 in April and again increased rapidly to the highest level in May. It decreased sharply to 5.2 in June and again increased rapidly to 12.7 in July. The N/P ratio decreased slightly in August and a sharp decline in September lead to the lowest level (3.3) in October. It increased very rapidly to 12.7 in November and similar levels remained throughout the rest of the period of study.

High N/P ratio during the spring was due to the low phosphorus content of seston (Fig. 49), originated mainly from the death and decomposition of littoral macrophytes during the previous winter. The summer peak during July and August could be related with very high concenrations of nitrogen in the seston originating both from living algae in the upper trap (Fig. 45) and high nitrogen content detritus from the death and decomposition of phytoplankton in the lower trap. High N/P ratio immediately after the autumn overturn in October in the upper trap and in November in the bottom trap was due to low phosphorus content of seston originating mainly from the resuspension of the sediment and long term decomposed detritus. In the bottom trap, high N/P ratio during the winter months was due to low phosphorus concentration in comparison with nitrogen content of seston, originated mainly from littoral macrophytes and allochthonous organic matter. Hallegraeff (1978) compared N/P ratio of three Dutch lakes which varied between 1.97 and 11.2 depending on the trophic status of Lakes. In the least productive Lake, constant low N/P ratio was the result of the low participation of algae in the total suspended particulate matter. The seasonal variations of N/P ratios in each Lake was directly related with the amount of phytoplankton present in the seston sample. During the present study, similar seasonal patterns of N/P ratio was

Figure 52. Seasonal variations of energy content per gram dry weight of seston from March, 1985 to February, 1986. The energy content is expressed in KJ x 1000/g of seston.

Energy content of seston



also observed in Dubh Lochan. It can, therefore, be suggested that N/P ratios of seston may be a potential "macroscopic" characteristics of the trophic dynamic status of lakes (Margalef, 1968).

6.3.9. Seston energetics :

6.3.9.1. Energy content per gram dry weight of seston :

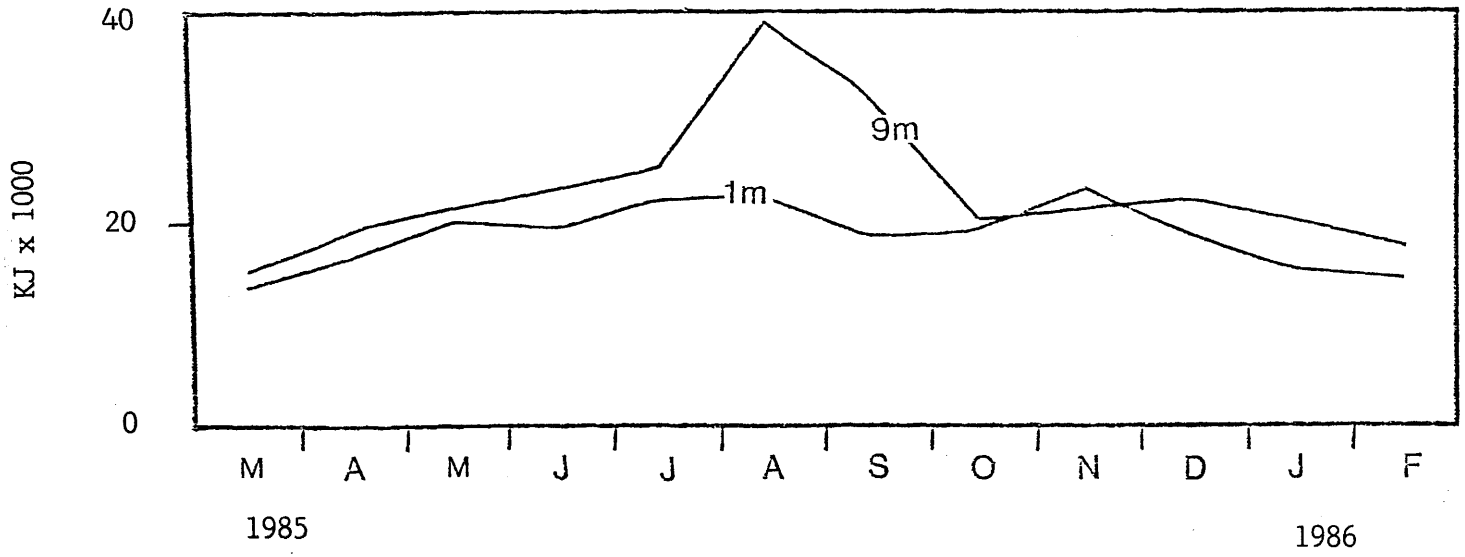
The energy content per gram dry weight of seston showed considerable variations both seasonally and vertically (Fig. 52).

In the upper trap (1m depth), energy content of seston ranged from 7.1 x 1000 to 14.9 x 1000 KJ/g. Seston energetics increased sharply from (8.4 x 1000 KJ/g) March and reached to the highest level (14.9 x 1000 KJ/g) in June and similar levels remained in July. It declined sharply in August and reached to 10.5 x 1000 KJ/g in September. From October energy content declined gradually to 9.0 x 1000 KJ/g in December. It declined sharply to 7.3 x 1000 KJ/g in January, 1986 and similar levels remained in February.

In the lower trap (9m depth), energy content ranged from 7.4 x 1000 to 13.9 x 1000 KJ/g. Energy content of seston was the lowest (7.4 x 1000 KJ/g) in March, it

Figure 53. Seasonal variations of energy content per gram ash free dry weight of seston from March, 1985 to February, 1986. The energy content is expressed in KJ x 1000/g of seston.

Energy content per gram ash free dry weight of seston



increeased slightly in April and then declined slightly in May. It increased sharply from (8.4 x 1000 KJ/g) May and reached to the highest level (13.9 x 1000 KJ/g) in August and similar levels remained in September. Seston energetics declined very rapidly in October and reached to (8.4 x 1000 KJ/g) in November and similar levels remained throughout the rest of the period of study .

6.3.9.2. Energy content per gram ash free dry weight of seston :

The energy content calculated on the basis of ash free dry weight of seston showed similar patterns of seasonal variations (Fig. 53) as was observed on dry weight basis (Fig. 52).

In the upper trap (1m depth), energy content per gram ash free dry weight varied between 13.7 x 1000 and 22.8 x 1000 KJ/g. The energy content was at the lowest level in March (13.7 x 1000 KJ/g), increased gradually through April and reached to 20.4 x 1000 KJ/g in May with increased production of phytoplankton. It declined slightly in June (18.8 x 1000 KJ/g) and then increased through July and reached to 22.3 x 1000 KJ/g in August. The energy content declined sharply in September (17.8 x 1000 KJ/g) and then a gradual increase through October lead to the highest level

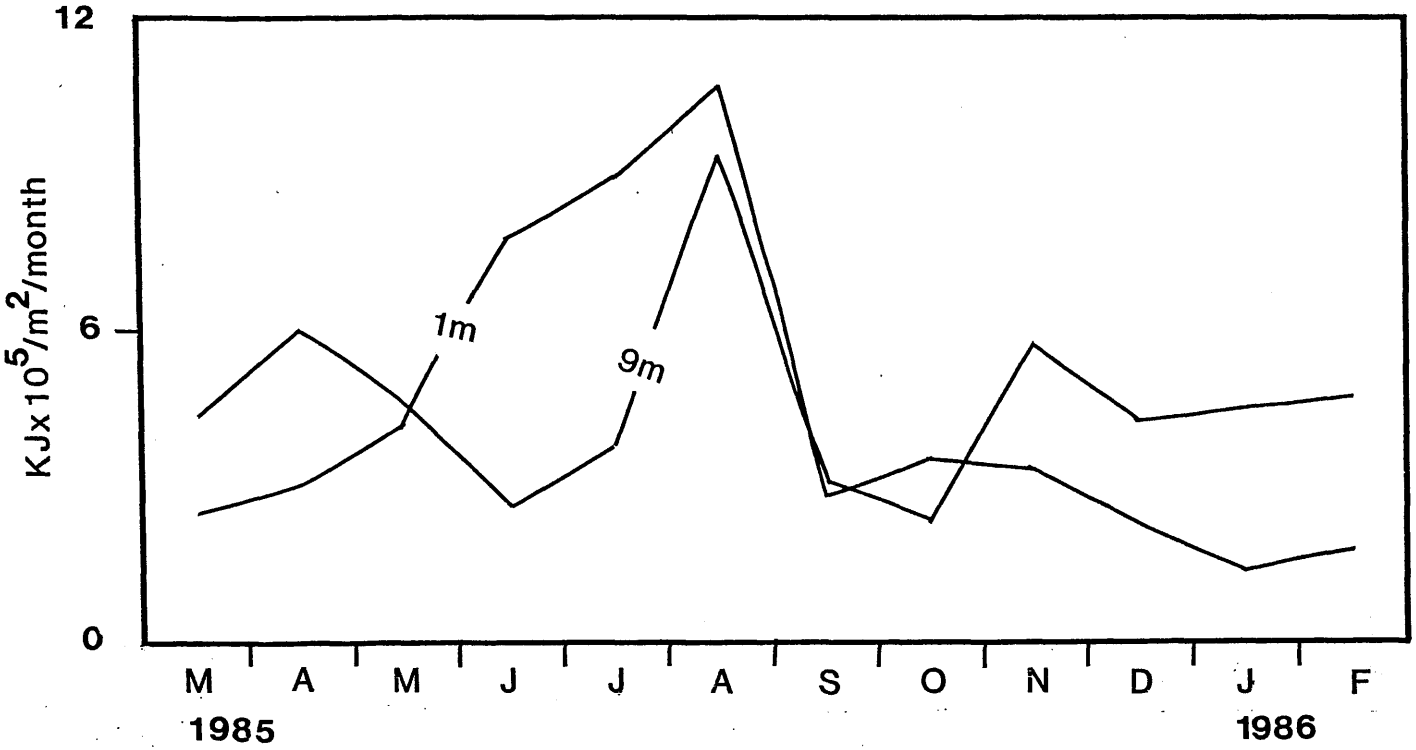
in November (22.8 x 1000 KJ/g). It declined gradually from December and reached to 14.5 x 1000 KJ/g in February, 1986.

In the lower trap (9m depth), the energy content ranged from 15.2 x 1000 to 39.5 x 1000 KJ/g. The energy content was also at the lowest level in March (15.5 x 1000 KJ/g), increased gradually through April and reached to 21.4 x 1000 KJ/g in May. It declined slightly in June (16.1 x 1000 KJ/g) and a sharp increase through July lead to the highest level in August (39.5 x 1000 KJ/g) when the hypolimnion was completely deoxygenated (Fig. 5). The energy content declined through September (31.5 x 1000 KJ/g) and October (20.2 x 1000 KJ/g) and again increased slightly in November (21.2 x 1000 KJ/g) and December (22.3 x 1000 KJ/g) and then declined gradually to 16.6 x 1000 KJ/g in February, 1986.

The highest energy content of seston in the upper trap during June and July was due to algal growth in the seston tubes (Fig. 45). High levels of energy from May to August could be related with high contribution of algal material in composition of seston (Fig. 45). Several workers reported that energy content of phytoplankton is considerably higher than organic detritus (Gorham and Sanger, 1967; Leach, 1975; Hallegraeff, 1978; Jonasson, 1979). Although the contribution of diatom was high from August to October, energy content of seston declined because the energy content

Figure 54. Seasonal variations of total energy content of seston from March, 1985 to February, 1986. The energy content is expressed in KJ x $10^5/m^2$ lake surface/month.

Total energy content of seston



of diatom is considerably less than other algae due to high ash content of diatom frustules (Hallegreff, 1978; Jonasson, 1979).

High energy content of seston in the lower trap from July to September could be related with high rate of bacterial decomposition in anaerobic condition (Fig. 5) at a time when organic detritus originated mainly from dead phytoplankton. Lastein (1976) reported that energy content of seston decrease in oxidized condition and increase in reduced condition (Moss, 1982) because of increased production of bacteria and fungi.

Low energy content of seston in March, 1985 and in January, 1986 and February in both the upper and lower traps could be due to low energy content organic detritus originating mainly from aquatic macrophytes and to certain extent from inorganic particles (Fig. 45) of high ash content (Hallegraeff, 1978).

6.3.9.3. Total energy content of seston

(KJ x $10^5/m^2$ lake surface/month) :

The seasonal variations of total energy content of seston (Fig. 54) observed close relationship with seston

biomass (Fig. 44) and showed considerable differences between the upper and lower traps.

In the upper trap (1m depth), total energy content of seston ranged from 1.47 x 10^5 to 10.71 x 10^5 KJ/m^2/month. It increased gradually from (2.36 x 10^5KJ/m^2/month) March and reached to the highest level (10.71 x 10^5KJ/m^2/month) in August. Total energy content of seston declined very rapidly (2.83 x 10^5KJ/m^2/month) in September and again increased slightly in October. It declined gradually from (3.3 x 10^5KJ/m^2/month) November and reached to the lowest level (1.47 x 10^5KJ/m^2/month) in January, 1986 and again increased slightly (1.78 x 10^5KJ/m^2/month) in February.

In the lower trap (9m depth), total energy content of seston ranged from 2.46 x 10^5 to 9.37 x 10^5 KJ/m^2/month. It increased from 4.48 x 10^5 KJ/m^2/month in March to 6.0 x 10^5KJ/m^2/month in April and then declined sharply to very low level (2.62 x 10^5KJ/m^2/month) in June. Total energy content increased slightly in July and then a very rapid increase lead to the highest level (9.37 x 10^5KJ/m^2/month) in August. It declined very sharply (2.87 x 10^5KJ/m^2/month) in September and then a slight decrease resulted in its lowest level (2.46 x 10^5KJ/m^2/month) in October. Total energy content increased sharply (5.28 x 10^5KJ/m^2/month) in November and again declined slightly (4.37 x 10^5KJ/m^2/month)

in December and similar levels remained during January, 1986 and February.

With increasing phytoplankton (Fig. 23) and primary production (Fig. 35), total energy content of seston in the upper trap increased gradually from March to May. Rapid increase in the total quantity of energy in the seston during June and July and the highest level in August was contributed by algal growth inside the seston tubes (Fig. 45) together with the highest production of phytoplankon throughout the water column in June and July. Although phytoplankton production was the highest and the energy content per gram of seston was high in June and July, total energy content in the lower trap declined with declining seston biomass (Fig. 44) which is related with sedimentation process of dead and decomposed phytoplankton (Moeller & Likens, 1978 and Lastein, 1983). Leach, (1975) reported that on a seasonal basis, the amount of detrital energy was smallest in summer in Lake Erie although the highest level was in late summer to early autumn. However, as the sedimented seston settled at the bottom, total energy content reached to the highest level in August with the highest level of seston biomass. Rapid decline of total energy content of seston in September is related with the

sharp decline of phytoplankton biomass from mid July to August.

After the autumn overturn and complete mixing of the water column (Fig. 3), total energy content of seston increased slightly in the upper trap in October and November and the rapid increase in the lower trap in November could be related with the settlement of resuspended organic matter from the flocculent layer of the sediment (Jonasson et al., 1974; Lastein, 1976). Low levels of total amount of energy in the upper trap during the winter months could be related with very low phytoplankton production and high input of mineral matter (Fig. 46) as well as low energy content allochthonous organic matter coming with rainwater through the inlets. Although the energy content per gram of seston was low during the winter months, comparatively higher levels of total energy in the lower trap than the upper trap could be due to high quantities of organic detritus originating mainly from the death and decomposition of submerged and emergent aquatic macrophytes.

CHAPTER — 7.

SEDIMENT

7.1. Introduction :

Sediment plays an important role in regulating freshwater ecosystems (Odum, 1971; Golterman & Kouwe, 1980; and Moss, 1982). In anoxic conditions which may occur in the hypolimnion during the summer months in temperate regions, the sediment releases nutrients, gases and other decomposition products into the water which are mixed throughout the water column during the autumn overturn (Hutchinson, 1957). The mechanism of chemical exchange between sediment and water in lacustrine ecosystem has been well documented and the followings are classic examples Jenkin et al.,(1941); Mortimer, (1941 -1942); Hayes et al., (1958); Kamp-Nielsen, (1974) and Gorham et al., (1974). The chemistry of sediment has been well studied and used in characterizing different types (Hutchinson & Wollack, 1940; Kleerekoper, 1955; Mackereth, 1955; Frink, 1969; Serruya, 1971; Gorham et al., 1974; Wildung et al., 1974; and Guppy & Happey-wood, 1978). Organic matter and particle size has long been used in characterizing the sediment (Hayes & MacAuley, 1959 ; Kemp, 1971; Hargrave, 1972; and Banin et al., 1974). Lake sediment controls the cycles and balance

of nutritional elements in the lake water (Banin et al., 1974) which could play a critical role in determining the trophic status of lakes (Golterman, 1966). Below the euphotic zone only heterotrophs can thrive, and they are totally dependant on detritus. Naumann (1921) stated that detritus and bacteria in the lake sediment must be the most important sources of food for a wide variety of detritivore organisms. Since then, many workers have emphasized the importance of sedimenting organic matter as a dominent source of food in aquatic ecosystems (Saunders, 1969, 1980; Cummins et al., 1973; Moss, 1982; and LeCren & Lowe-McConnell, 1980).

Sediments yield valuable information about production and mineralization throughout the water column in lakes (Hargrave, 1973). Resuspension of organic particles from the sediment associated with turbulance probably occurs more or less continually in lakes (Westlake et al., 1972) except the summer stagnation period in deep water. There may be periodic resuspension, lateral transport, sorting and deposition into the pelagic region of lakes (Wetzel et al., 1972). There are also resuspension periods in lakes with mass overturn during spring and autumn in the lakes of temperate and high altitudes (Saunders, 1980). Such resuspensions are very important in the functions of lacustrine ecosystems. The growth of benthic filter feeding

detritivores is correlated with sedimentation of organic detritus during the spring and autumn (Jonasson, 1972; Pennington, 1974; and Kirchner, 1975). McLachlan (1969) concluded that the nature and distribution of the benthic fauna are strongly influenced by the characterestics of the sediment.

Metabolism of detrital and particulate organic carbon, which occurs largely in the sediment, provides stability in the ecosystems (Wetzel, 1975).

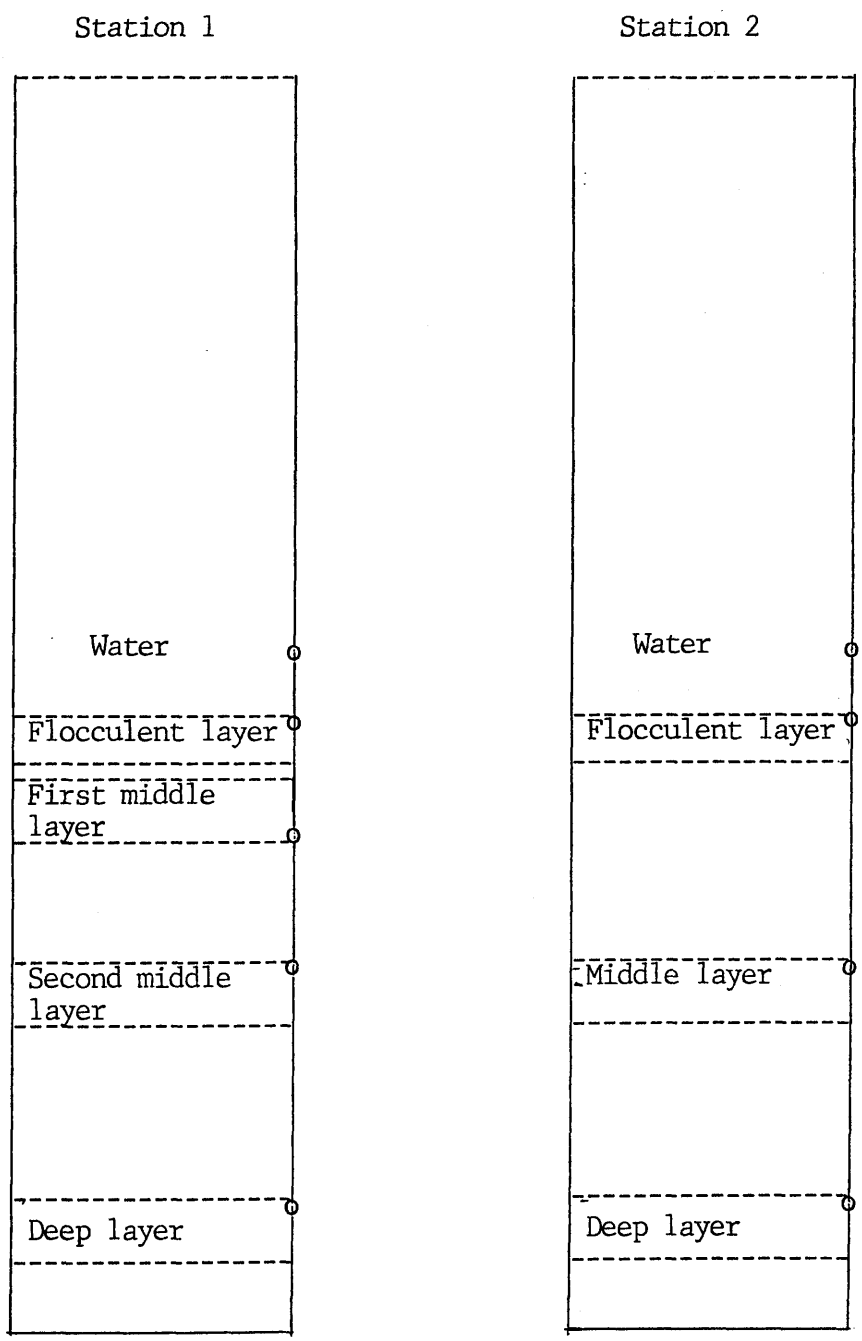
Organic matter in the sediment functions as an energy reservoir, which may be more rapidly or more slowly utilized, depending on the functional requirements of the system. It also contains the elements that enter in to the construction of living protoplasm, when it is decomposed due to bacterial activities, these elements are released and become available for storing energy in the form of new protoplasm.

7.2. Materials and Methods :

7.2.1. General :

Undisturbed sediment cores were taken from station 1 (deepest part of the lake where the sediment surface is

Figure 55. Sediment cores from station 1 and station 2 showing different layers where the subsamples were taken for routine analysis.



completely deoxygenated during the late summer) and station 2 (5m deep, where the sediment surface is always well oxygenated but still below the euphotic zone) from July, 1985 to June, 1986 using a Jenkin mud sampler. The sediment collection tubes fitted with the sampler were drilled with 4mm holes, at 1 cm intervals along the vertical axis and were sealed with PVC tape. The samples were collected every fortnight from July to November, 1985 and once in a month from December to June, 1986. They were carried to the laboratory in a wooden case immediately after collection and extreme care was always taken to prevent any mixing of the sediment during transportation. The supernatant water was siphoned very carefully with a thin plastic tube. Subsamples of sediment were taken through the holes of the sediment tubes with the help of a Cyringe (B-D plastipak, 20ml capacity) from different layers with minimum disturbance (Fig. 55). Four subsamples were taken from the sediment collected from station 1 as flocculent layer (top 1cm), first middle layer (2cm from the top), second middle layer (4cm from the top) and deep layer (8cm from the top). The flocculent layer is mainly brown detritus mud of about 1cm thickness. The first middle layer is black oozy mud of about 2 - 3cm thickness. The second middle and deep layer is also black oozy mud but no distinct layers were observed. The flocculent layer receives the sedimented seston. This seston is probably metabolized in the middle layer where chemical

exchange between mud and water takes place and also most of the benthic organisms live. The deep layer may not be involved in such processes. Three subsamples were taken from the sediment collected from station 2 although no distinct layers were observed. However, they are also referred as flocculent layer (top 1cm), middle layer (4cm from the top) and deep layer (8cm from top). Each subsample was filtered through GF/A filter paper to remove the remaining water and dried in an oven at 110°C for 4 hours to get a constant dry weight of the sediment.

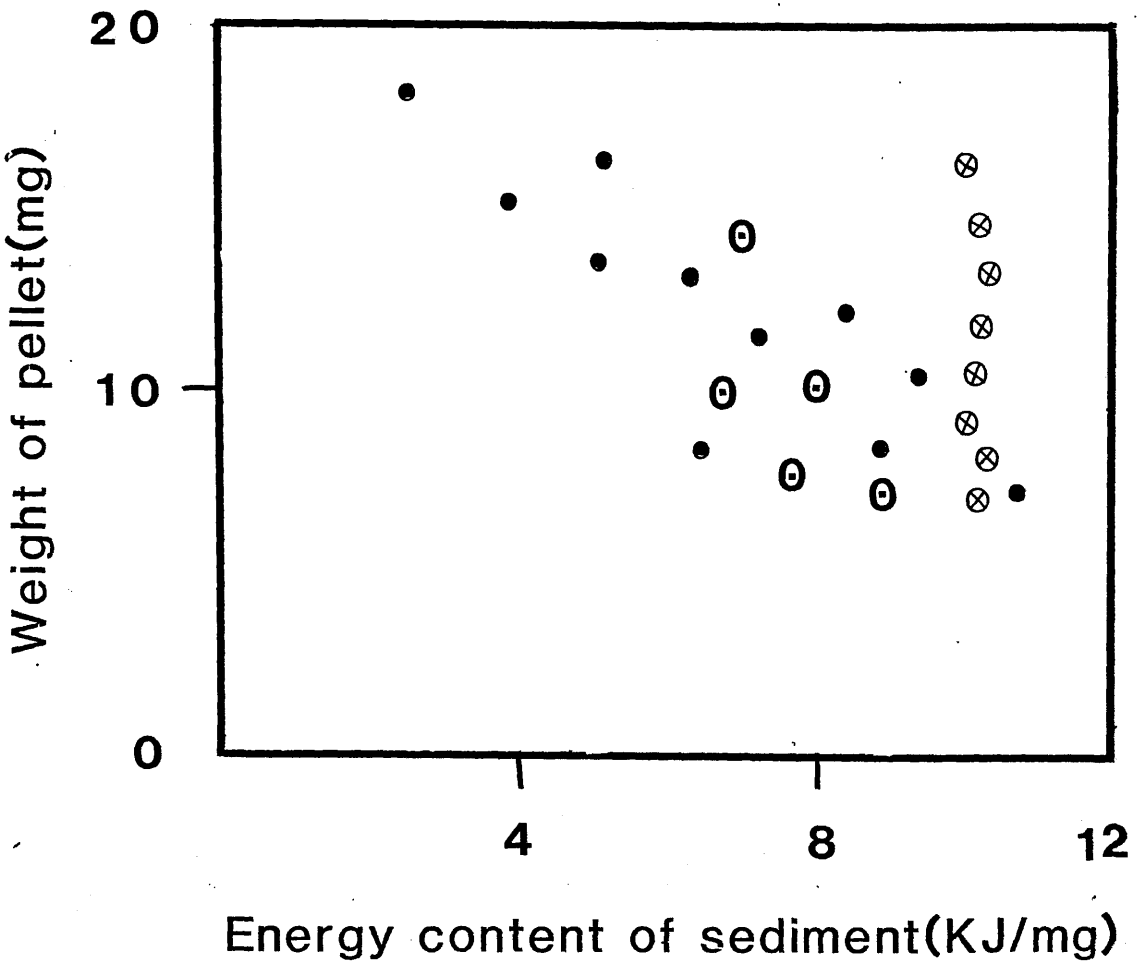
7.2.2. Organic & mineral content, carbon, total nitrogen and soluble reactive orthophosphate :

Organic & mineral content, carbon, total nitrogen and soluble reactive orthophosphate were determined according to the methods described earlier in Chapter 6 for seston analysis.

7.2.3. Sediment energetics :

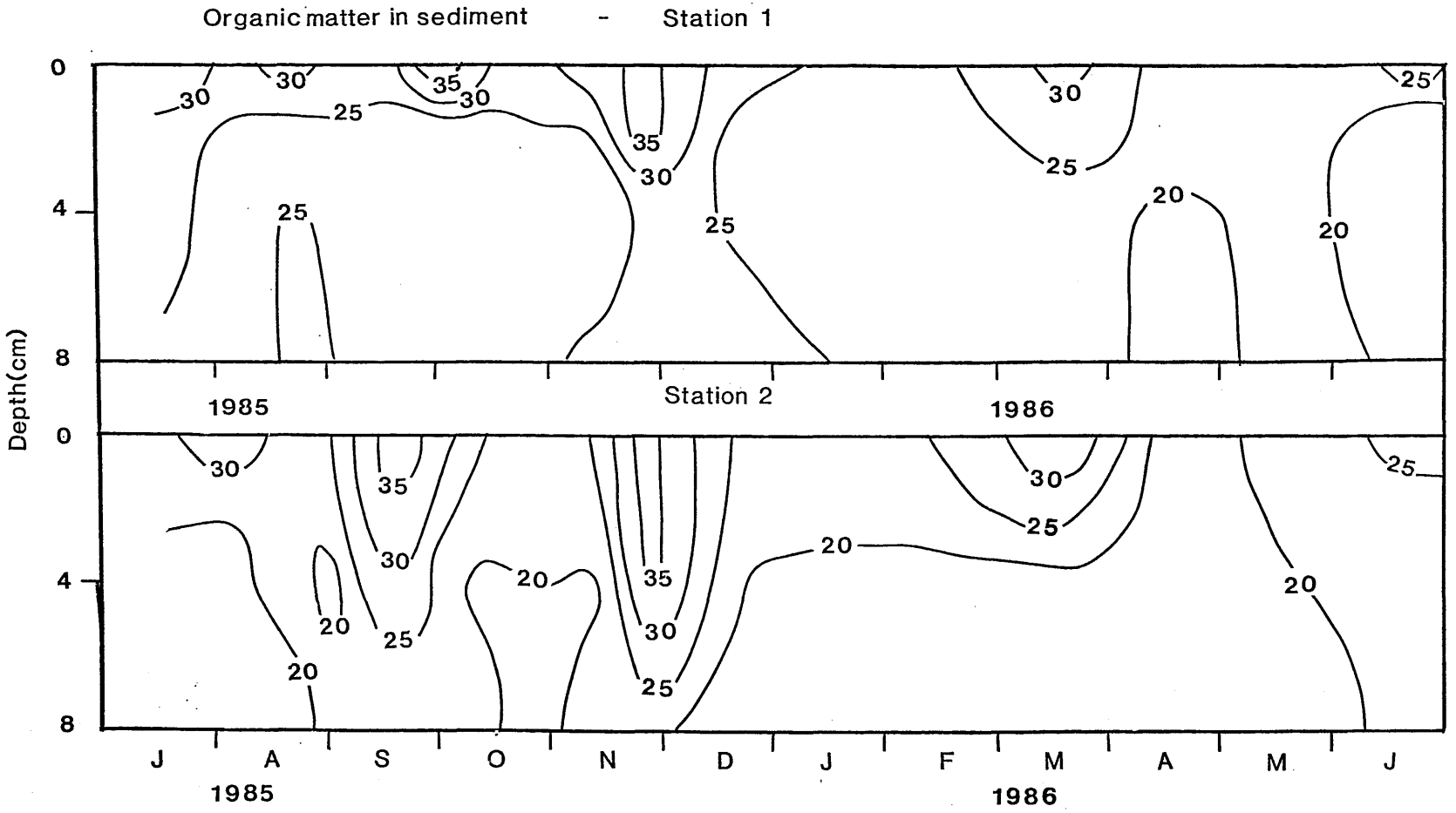
The energy content of the oven dried (110°C for 4 hours) sediment samples were determined using a microbomb Calorimeter (Model AH 12 EF 2). Pellets made entirely of sediment failed to ignite because of the high mineral content (Fig. 58), ranging from 65 to 80%. To increase the

Figure 56. The relationship between pellet size and the combustability of the sediment.


20
10
0
Weight of pellet(mg)
4
8
12
Energy content of sediment(KJ/mg)

combustability of the sediment, it was necessary to mix the samples with dried Analar grade Benzoic acid as suggested by Gorham & Sanger (1967). Benzoic acid is highly combustable and has a known calorific value (26.56 KJ/mg). After mixing the sediment samples with Benzoic acid, they were always kept in a desiccator because Benzoic acid absorbs moisture which may increase the weight of the sample. In an experiment to determine the correct proportions to use, it was found that with 2 parts Benzoic acid and 1 part sediment, the combustion was negatively correlated with pellet size (Fig. 56). The combustability increased with 3 parts Benzoic acid and 1 part sediment but negative correlation still existed. At a proportion of 4 parts Benzoic acid and 1 part sediment, the energy content was independant of pellet size and the sample to sample variation was minimum (S. D. ± 0.089 KJ/mg). The energy content of the sediment samples were therefore, determined after mixing with 4 parts Benzoic acid. All the samples were analyzed in duplicate and the mean standard deviation is ± 0.093 KJ/mg. The energy content of the pellets was calculated with an appropriate calibration curve made with Benzoic acid. The energy content of the sediment was then calculated by subtracting the value for Benzoic acid mixed with the samples and were finally expressed as Kilo Joules per gram of sediment. The top 1cm of the sediment from both station 1 and station 2 were used on a monthly basis for the

Figure 57. Seasonal variations of organic matter in the sediment from July, 1985 to June, 1986. Organic matter is expressed as percentage.


Organic matter in sediment - Station 1
Depth(cm)
0
4
8
30
25
35
20
1985
Station 2
1986
J
A
S
O
N
D
J
F
M
A
M
J
1985
1986

determination of energy content in the sediment. This is the part of the sediment in dynamic contact with the water of the lake.

7.3. Results and Discussion :

7.3.1. Organic and mineral content (Percentage loss on ignition) :

Organic matter in the sediment evaluated by the loss on ignition method showed little variation both seasonally and vertically (Fig. 57).

In deep water at station 1, organic matter ranged from 20 to 35%.

In the flocculent layer, concentrations were generally slightly higher than the middle and deep layer. From July to mid December, organic matter remained around 30% except in late September to early October and in late November when it reached to 35%. The concentrations remained around 25% from late December to June, 1986 except in mid March when it increased to 30%.

In the first middle layer (2cm from top), organic matter remained between 25 and 30% from July to mid December

except in late November when it increased to 35%. From late December to May, 1986, the concentrations remained around 25% and then declined to 20% in June.

In the second middle layer (4cm from top) and deep layer (8cm from top), organic matter remained around 25% from July to mid January, 1986. it declined gradually to 20% in April and similar levels remained up to June.

At station 2, organic matter ranged from 20 to 35%.

In the flocculent layer, organic matter showed similar seasonal patterns as was observed at station 1. The highest concentration (35%) was observed in September and in late November to early December and the lowest level (20%) was observed from mid April to mid May.

In the middle layer (4cm from top), organic matter ranged from 20 to 30 %. The concentrations remained around 20% during most of the period except September when it increased to 25% and in late November to early December when it reached to 30%.

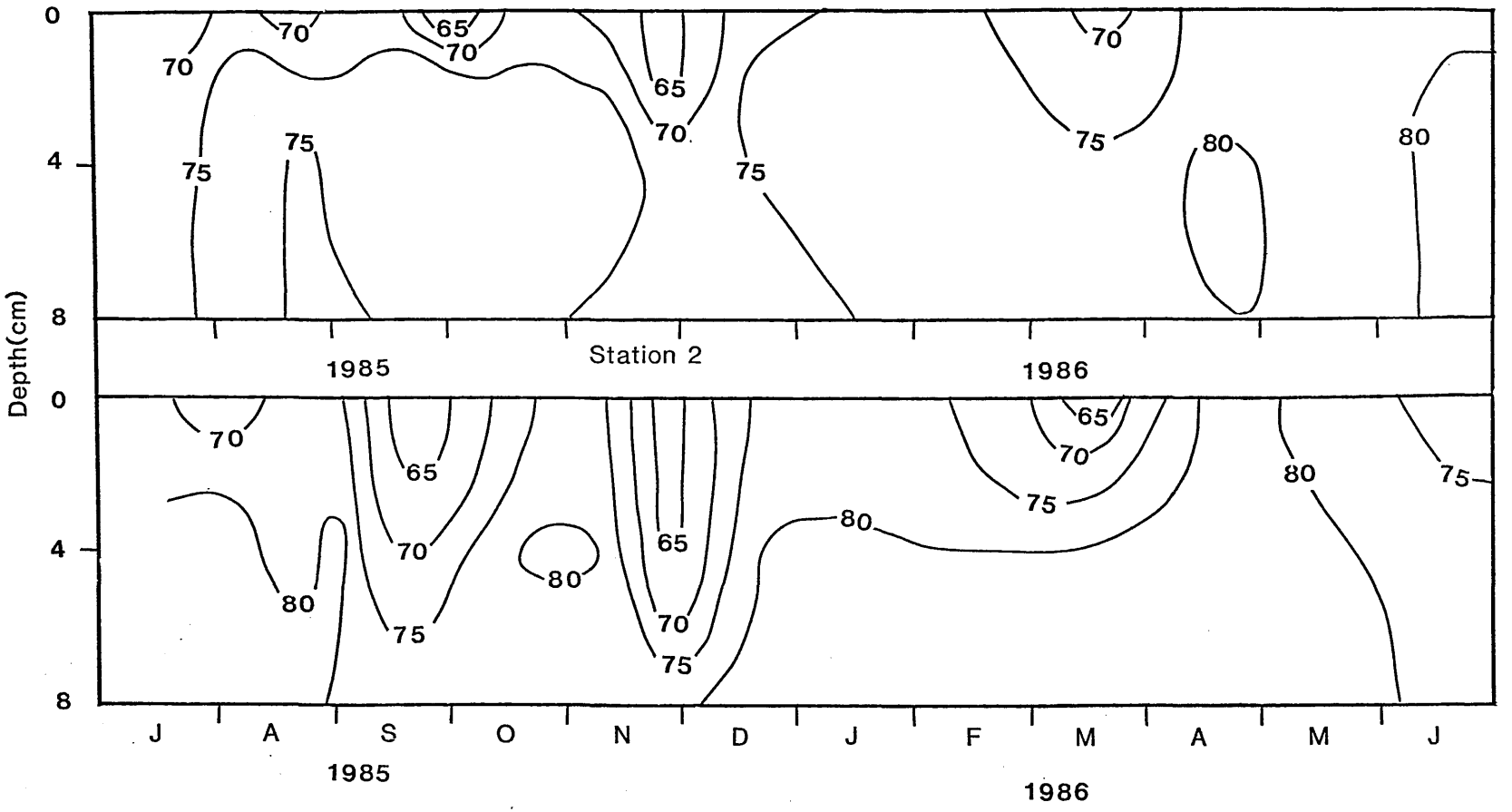
In the deep layer (8cm from top), organic matter remained around 20% during the whole period of study.

Organic matter in the flocculent layer did not vary significantly between the two stations. Clay & Wilhm (1979) also reported similar observations of organic matter between shallow and deep stations in Ham's lake in U. S. A. Kemp (1971) reported that the quality of organic matter in the top centimetre of the sediment was directly proportional to clay size fraction of sediment and independant of depth, rate of sedimentation and degree of eutrophication. In the present study, the highest level of organic matter in the flocculent layer in both the stations is related with the continuous supply of sedimentary seston. High level during the summer months at station 1 could be related with bacterial decomposition particularly under anaerobic condition (Fig. 5) at a time of high seston production (Fig. 44). The highest level in November was probably due to the resettlement of the organic matter after the resuspension during autumn overturn.

In shallow water decomposing macrophytes and leaf litter generally contribute significant quantities of organic matter in the sediment (Clay & Wilhm, 1979). In the present study, seston biomass (recorded at station 1 only) during late summer and autumn were also high (Fig. 44), which could well be accounted for high organic content in the flocculent layer of the sediment. High levels of organic matter in the middle layer where the sedimented seston are further

Figure 58. Seasonal variations of mineral content in the sediment from July, 1985 to June, 1986. Mineral content is expressed as percentage.

Mineral content of sediment - Station 1



decomposed and processed by bacteria and zoobenthos seems to be reasonable and similar patterns of seasonal variations as was observed in the flocculent layer is expectable. Highest level of organic matter during the summer months and high levels during the spring and autumn in different lakes have been reported by several workers (Hargrave, 1972; Clay & Wilhm, 1979 and Polunin, 1982). The percentage of organic matter in the deep layer was much lower than the flocculent and middle layers and the values were almost constant throughout the year which indicate that this part of the sediment was not interacting with the metabolism of the lake.

The mineral content of the sediment were always very high ranging from 65 to 80%. It did not vary significantly between the two stations and the seasonal and vertical variation was slight (Fig. 58).

In deep water at station 1, the mineral content in the flocculent layer ranged from 65 to 75% and was always lower than the middle and deep layer. From October to early December, the mineral content was around 70% except in late September to early October and in late November when it declined to 65%. From late December to the rest of the period, it remained around 75% except in late March when it declined to 70%.

In the first middle layer (2cm from top), it remained around 75% during most of the time except in late November when it declined to 65% and in mid June when it increased to 80%.

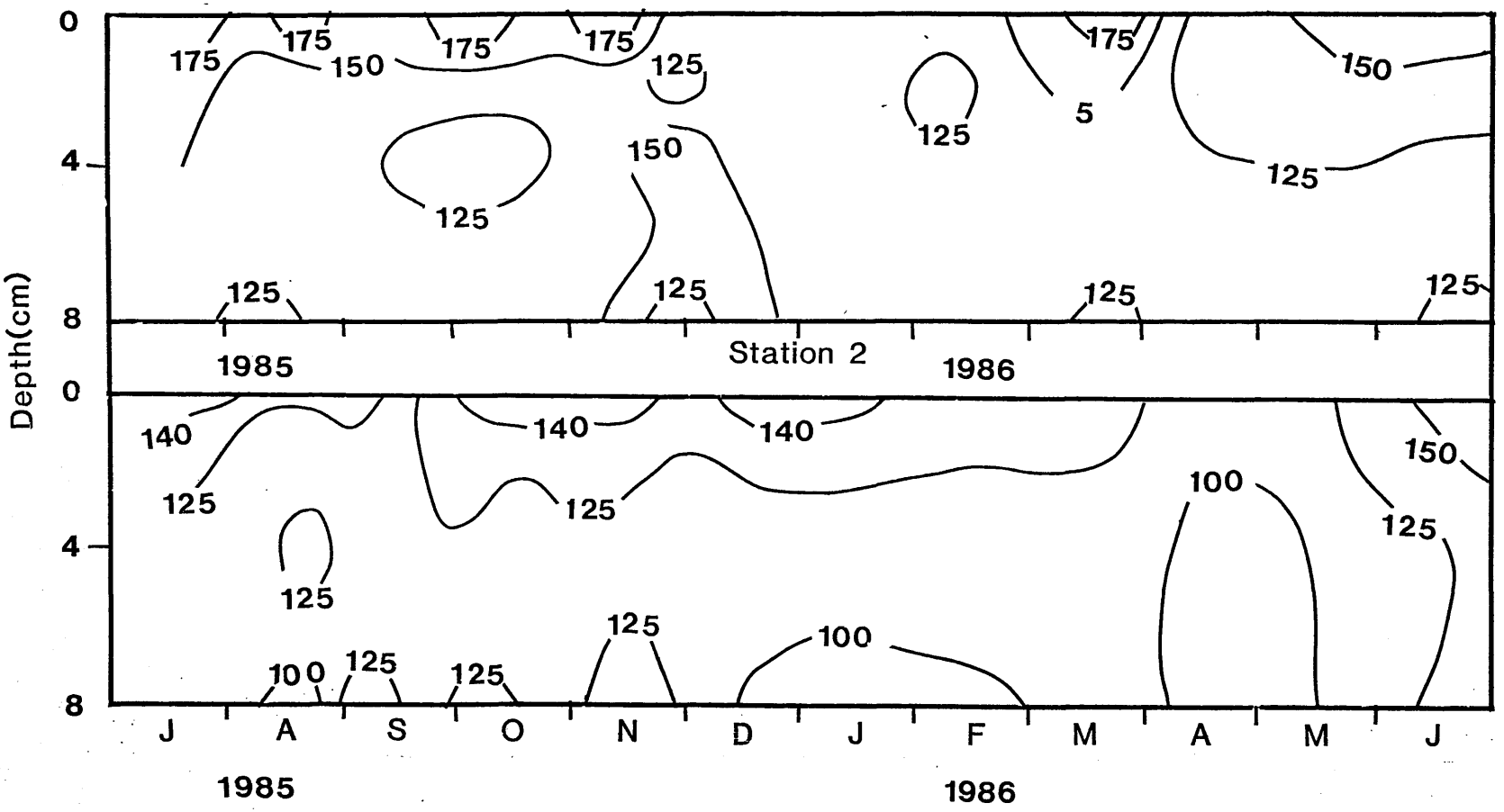
In the second middle layer (4cm from top) and deep layer (8cm from top), the mineral content remained around 75% from July to mid January, 1986, it increased gradually to 80% in late April and similar levels remained during the rest of the period.

At station 2, mineral content in the flocculent layer ranged from 65 to 80%. It varied between 70 and 75% during most of the time except mid September, late November and mid March when it declined to 65% and in mid April to early March when it increased to 80%.

In the middle layer (4cm from top), the mineral content remained around 80% during most of the time except in September when it declined to 75% and in late November to early December when it reached to 70%. In the deep layer (8cm from top), mineral content always remained around 80%.

Figure 59. Seasonal variations of carbon content in the sediment from July, 1985 to June, 1986. Carbon content is expressed in mgC/g of seston.

Carbon content of sediment - Station 1



7.3.2. Carbon content (loss on ignition) :

The carbon content of the sediment showed great seasonal and vertical distribution patterns with highest level in the flocculent layer. Considerable differences were also observed between the two stations (Fig. 59).

In deep water at station 1, carbon content in the flocculent layer remained high (175mg/g) from July to mid September. It increased rapidly to the highest level (225mg/g) in late September to early October. Carbon content declined gradually to 150mg/g in late November and similar levels remained up to late February, 1986. It increased to 175mg/g in mid March and then declined to 125mg/g in mid April and again increased to 150mg/g in early May and similar levels remained till June.

In the first middle layer, carbon content remained between 140 and 150mg/g during most of the time except in late November to early December, early February, 1986 and mid April when it declined to 125mg/g.

In the second middle and deep layer carbon content remained almost constant to 125mg/g except in mid July and from late November to late December when it increased to 150mg/g.

At station 2, carbon content of the sediment were always lower than station 1 and ranged from 100 to 150mg/g.

In the flocculent layer carbon content remained approximately 140mg/g from July to early September. It declined to 125mg/g during mid to late September and again increased to 140mg/g in early October and similar levels remained up to January, 1986. It declined gradually to 125mg/g in early April and similar levels remained till late May and again increased to the highest level (150mg/g) in June.

In the middle layer, carbon content was almost constant to 125mg/g except in mid April to mid March when it declined to 100mg/g.

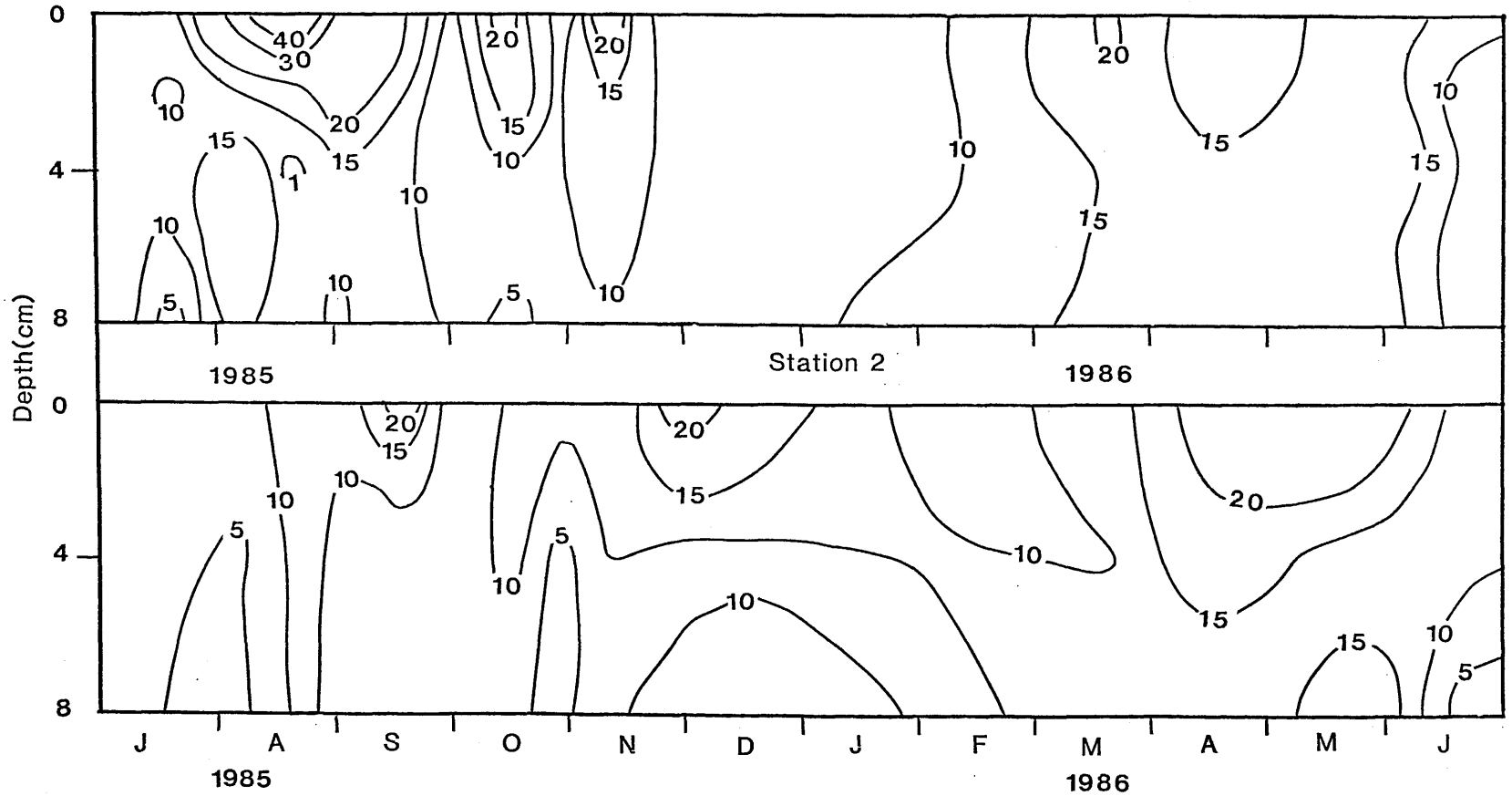
In the deep layer, carbon content was approximately 100mg/g from July to August, it increased to 125mg/g in September and similar levels remained till November. It declined to 100mg/g in December and similar levels remained up to May and again increased to 125mg/g in June.

High values of carbon in the flocculent layer of the sediment at station 1 during the summer and mid spring is related with the supply of organic seston (Fig. 44)

originated mainly from algal material. The highest level during late September to early October could be related with anaerobic decomposition of organic matter. The sediment surface at station 2 was always well oxygenated (Fig. 6) and the highest level in June could also be related with the supply of organic seston but high levels from October to March could be related with non-algal organic seston particularly from the decomposition of aquatic macrophytes which may well account for lower carbon values than the sediment at station 1. Gorham & Sanger (1967) reported that carbon content of organic matter in the sediment receiving algal material is much higher than those receiving organic matter from aquatic macrophytes. Carbon content of the sediment is well documented and spring, summer and autumn maxima in different lakes seem to be common (e.g. Clay & Wilhm, 1979; Guppy & Happey-Wood, 1978; Lastein, 1976; Polunin, 1982 and Storr et al., 1984). Slack (1954) studied the bottom deposit of Loch Lomond and reported that carbon content of deep water sediment were always higher than the littoral and littori-profundal sediment. The highest carbon content in the flocculent layer and the decline with the depth of the sediment in both the stations could be related with larger autochthonous component and increased consumption, especially at deeper levels, by bacteria and benthic animals as well as modifications by mechanical disturbances at the surface, known to take place during

Figure 60. Seasonal variations of total nitrogen concentrations in the sediment from July, 1985 to June, 1986. Nitrogen concentration is expressed in mg NH_4 - N/g.

Total nitrogen concentration in the sediment - Station 1



winter gales (Slack, 1954). The highest level of carbon in the top centimetre and decrease with the depth of the sediment seems to be common in most lakes (e.g. Lastein, 1976; Mackereth, 1966; Pennington, 1973).

7.3.3. Total nitrogen :

Total nitrogen concentrations in the sediment showed marked seasonal and vertical variations. Great differences were also observed between the two stations (Fig. 60).

In deep water at station 1, total nitrogen concentrations of the sediment ranged from 5 to 53.4mg/g. In the flocculent layer (top 1cm), the concentrations increased gradually from 10mg/g in July, 1985 with decreasing oxygen saturation in the hypolimnion (Fig. 5) and reached to the highest level of approximately 53.4mg/g in late August when the sediment surface was completely deoxygenated. As thermal stratification began to breakdown and oxygen saturation at the sediment began to increase from early September, 1985, total nitrogen concentrations declined rapidly and again reached to 10mg/g during late September to early October with autumn overturn and complete oxygenation of the bottom sediment. The concentrations increased to 20mg/g in mid October, declined slightly in late October to early November and again increased to 20mg/g in mid November. It declined

gradually to 10mg/g in late November and similar concentrations remained up to mid February. The concentrations increased gradually from late February, 1986 and reached to 20mg/g in mid March and again declined to 15mg/g in early April and similar levels remained during the rest of the period of study.

In the first middle layer (2cm from top) of the sediment, nitrogen concentrations showed similar patterns of seasonal variations as was observed in the flocculent layer. It varied between 10mg/g in early July and 40mg/g in late August to early September. During the rest of the period, the concentrations ranged from 10-15mg/g.

In the second middle layer (4 cm from top), total nitrogen concentrations varied between 10 and 15mg/g and the seasonal patterns were rather reversed. From mid July to mid August, the concentrations were approximately 15mg/g, it declined to 10mg/g in late August and similar levels remained until mid February, 1986. The concentrations gradually increased to 15mg/g in early March and similar levels continued up to early June and again declined to 10mg/g in mid June.

In the deep layer (8cm from top), the concentrations ranged from 5-15mg/g. The lowest concentration was observed

in mid June and mid October. The seasonal patterns were similar to the second middle layer of the sediment.

In the shallow water at station 2, total nitrogen concentrations in the sediment ranged from 4.1 - 21.2mg/g. Unlike station 1, nitrogen concentrations did not show a major summer peak because the sediment surface was always well oxygenated and the oxygen level never dropped below 55% saturation (Fig. 6).

In the flocculent layer, the concentrations ranged from 10-21mg/g. It showed three distinct and almost equal peaks (20mg/g) in mid September, late November to early December and from early April to early June.

In the middle (4cm from top) and deep layer, the concentrations ranged from 5-15mg/g. Both seasonal and verical distribution patterns were similar to station 1.

The highest concentrations of total nitrogen in the sediment in deep water at station 1, was due to the reduction of mud surface at a time when the seston biomass was at the highest level (Fig. 44), originating mainly from the summer phytoplankton bloom (Fig. 23). Remarkable changes occurred in the sediment as soon as the oxygen concentration in the hypolimnion dropped below detectable

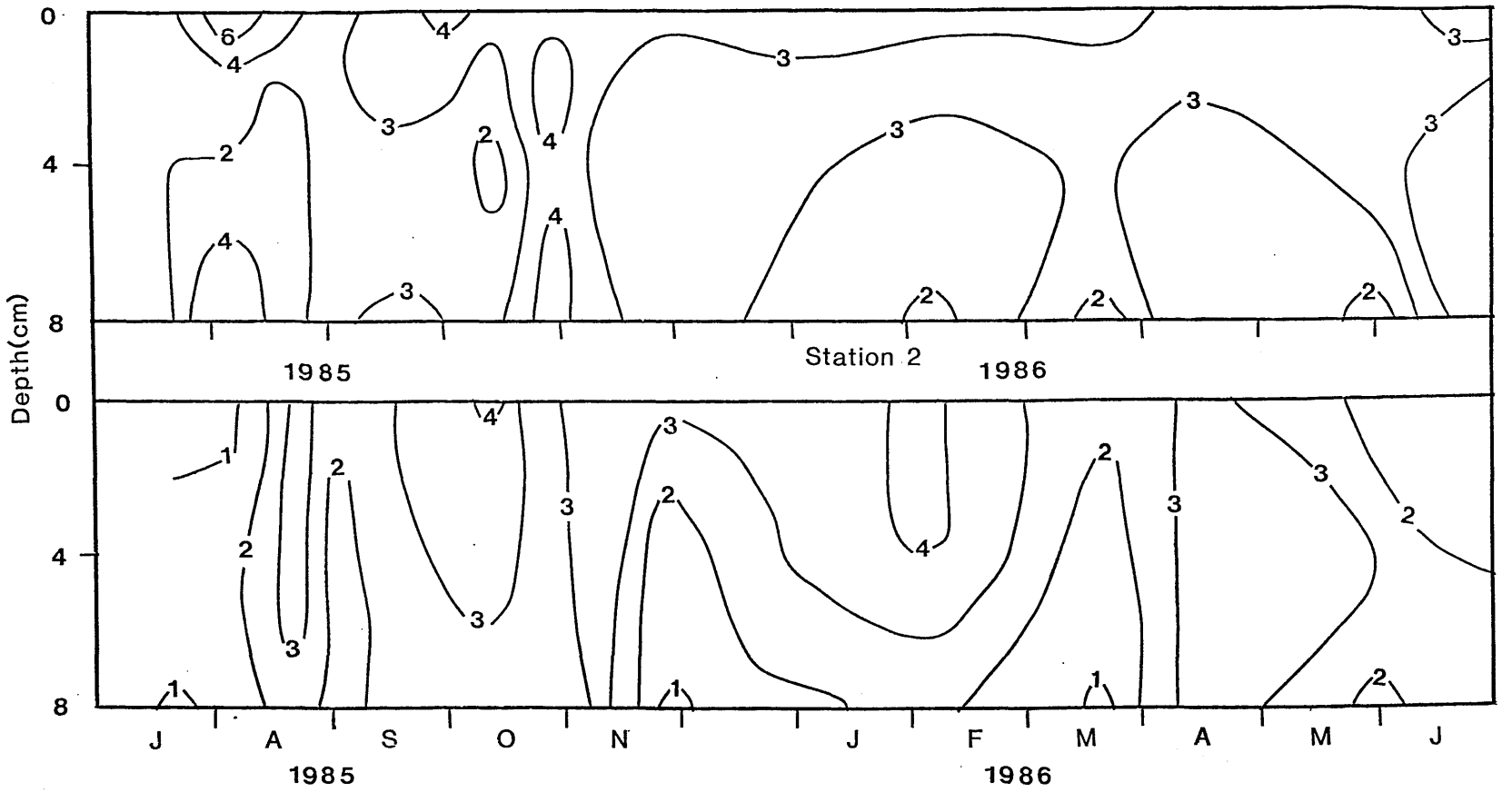
level. Rapid increase of total nitrogen concentrations during late summer in deep water sediment at station 1 suggest that at least some of the nitrogen was mobilized from the deep sediment in the form of ammonia. Mortimer (1941-1942) beautifully demonstrated the release of ammonia and other dissolved substances from the sediment and the exchange of ions between mud and water during hypolimnetic anoxia. Mortimer (1971) reviewed the probable regulatory mechanisms of chemical exchanges between sediments and water and suggested that reduction permits not only mobilization of ions but it also removes a barrier to free diffusion across the sediment water interface. The above changes were rapidly reversed when the mud surface was oxygenated during the autumn overturn.

The rise in total nitrogen concentrations in the flocculent layer of the sediment during October and November, 1985, could be realated with the resettlement of the organic matter after the autumn overturn which was also reflected in the total biomass of seston (Fig. 44).

The other minor peak during the spring in 1986 is related with the high organic matter content of the sediment derived mainly from the sedimentation of organic seston dominated by diatoms (Fig. 45). Gorham et al., (1974) observed similar phenomena and reported positive

Figure 61. Seasonal variations of total soluble reactive orthophosphate concentrations in the sediment from July, 1985 to June, 1986. Orthophosphate is expressed in mg PO4 - P/g.

Orthophosphate concentration in the sediment - Station 1



contribution of algae in the nutrient concentrations in the surface layer of the sediment in some English lakes.

The total nitrogen concentrations decreased with increasing depth of the sediment especially from July to September which was associated with the reducing condition in anoxic situation. However, small vertical variations during autumn and spring could be related with the nature and composition of the upper layer of the sediment. Guppy and Happey-Wood (1978) reported that total nitrogen concentrations in the sediment decrease with the increasing depth of the sediment.

7.3.4. Total soluble reactive orthophosphate :

Total soluble reactive orthophosphate concentrations in the sediment (Fig. 61) showed similar patterns of seasonal variation as was observed in total nitrogen concentrations (Fig. 60).

At station 1, orthophosphate concentration in the flocculent layer was approximately 2.72mg/g in early July. As soon as the oxygen saturation dropped below detectable level (Fig. 5), the concentrations increased sharply from mid July and reached to the highest level (7.42mg/g) in early to mid August. During this period, orthophosphate

concentrations in the hypolimnion also increased to the highest level (Fig. 17). As thermal stratification began to breakdown and the sediment surface was slightly oxidized, orthophosphate concentrations declined sharply to approximately 3mg/g in mid September. After the autumn overturn and resettlement of organic seston, the concentrations increased to 4mg/g during October and early November. The concentrations remained between 3 and 4mg/g from late November to early April, 1986. From mid April to the rest of the period of study, orthophosphate levels remained around 3mg/g.

In the first middle layer (2cm from top), orthophosphate concentrations ranged from 1.6 to 5mg/g and the seasonal patterns were similar to the flocculent layer.

In the second middle layer (4 cm from top), orthophosphate concentrations ranged from 1.9 to 3.7mg/g. The concentrations remained around 2mg/g from July to mid October. It increased to the highest level in late October to early November and remained around 3mg/g from mid November to the rest of the period of study.

In the deep layer (8 cm from top), orthophosphate concentrations ranged from 2 to 4mg/g showing small irregular fluctuations. The highest concentrations were

observed during late July to mid August and from late October to early November and the lowest levels were observed in early February, late March and in late May to early June.

Unlike station 1, orthophosphate concentrations in the sediment at station 2, did not show a late summer maximum because the sediment surface was always well oxygenated (Fig. 6). However, the concentrations ranged from 0.9 to 4.2mg/g.

In the flocculent layer, the lowest level of orthophosphate was observed in July to early August, it increased to 3mg/g in late August to late September and reached to the highest level in mid October. From late October to mid January, 1986, the concentrations remained around 3mg/g and again increased to 4mg/g in late January to early February. The concentrations again declined to 3mg/g in late February and similar levels remained up to late April. It declined gradually from early May and reached to 2mg/g during late May and early June. In the middle layer (4cm from top), orthophosphate concentrations ranged from 1.2 to 3.1mg/g and the seasonal patterns were similar to the flocculent layer.

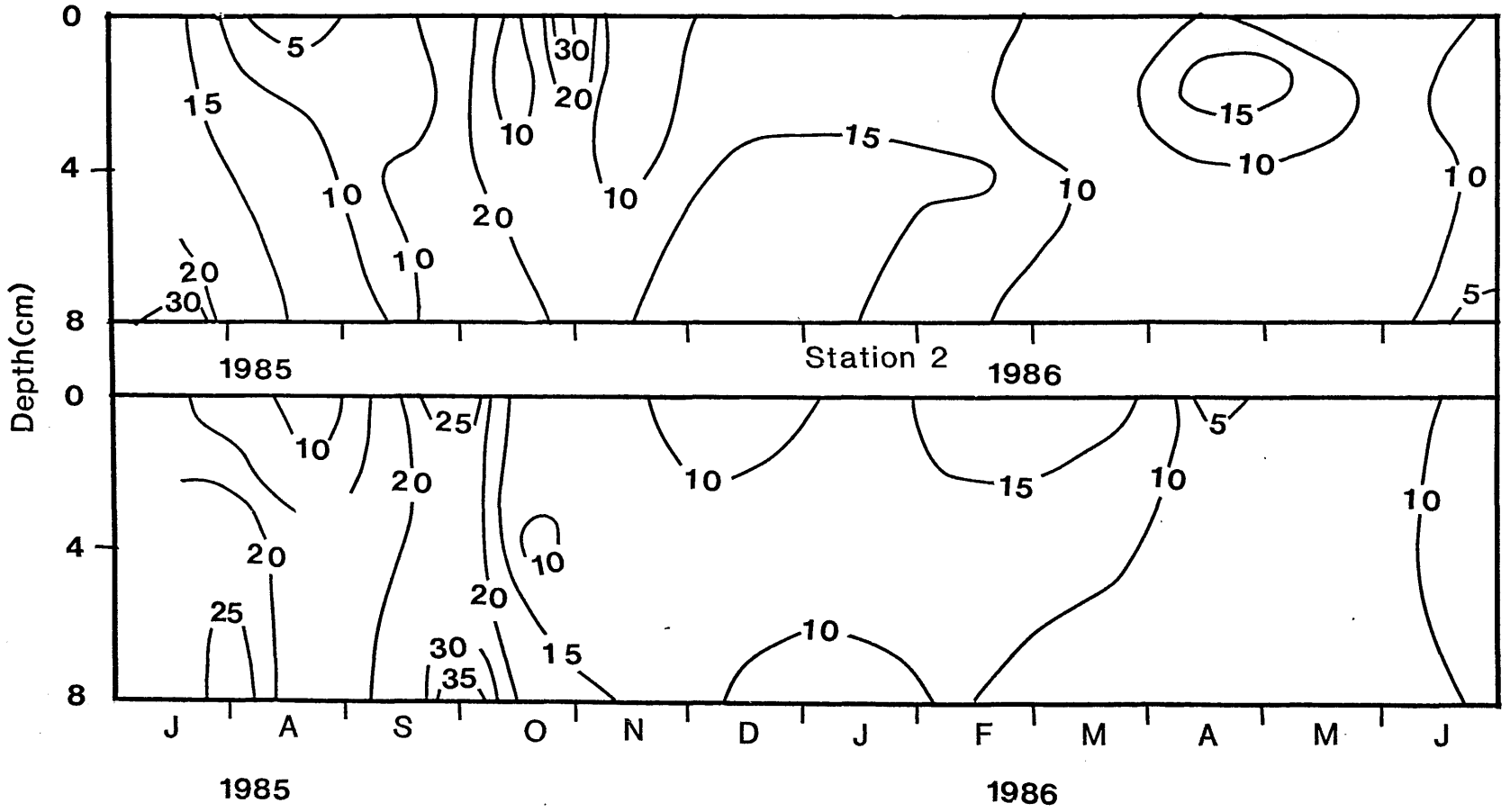
In the deep layer (8cm from top), orthophosphate

concentrations were generally low during most of the time and ranged from 0.98 to 3mg/g. The lowest concentrations were observed in July, late November to early December, mid March, 1986 and late May to early June. The highest concentrations were observed in early November, April and early May.

The exchange of nutrient ions across the sediment surface in lakes are mainly governed by temperature and sedimentation of organic seston (Kamp-Nielsen, 1975). The summer maximum in primary production during June and July (Fig. 35) was followed by the highest production of organic seston in late July to August (Fig. 44). Due to increasing surface and bottom temperature in this period, sediment surface was completely deoxygenated and anaerobic decomposition of the sedimented organic matter accelerated which was reflected in the maximum release of phosphate in to the overlying water (Fig. 17). The stimulating effect of sedimented organic matter in the exchange process of phosphate were reported by Gunatilka (1978) and Tessenow (1972). In deep water sediment at station 1, the increase of phosphate in the flocculent layer during hypolimnetic anoxia could also be due to mobilization from the deep sediment. However, in profundal sediment, the liberation of phosphate during summer stagnation is well documented (e.g. Mortimer, 1941-42; Kamp-Nielsen,1974; Banin et al., 1975; Guppy &

Figure 62. Seasonal variations of Carbon/Nitrogen ratio in the sediment from July, 1985 to June, 1986.

Carbon/Nitrogen ratio in the sediment - Station 1



Happey-Wood, 1978; Skogheim, 1978; Clay & Wilhm, 1979).

The increase of phosphate in the flocculent layer of the sediment in shallow water at station 2 could be due to redistribution of phosphate from the water after overturn, supplemented from the deep water sediment.

Phosphate concentrations showed very small fluctuations both seasonally and vertically during most of the time in both the stations except the summer stagnation period in deep water sediment in Dubh Lochan. Similar observations were also made by Boers et al., (1984). Kamp-Nielsen (1975) reported that a steady fixation of phosphate takes place in the littoral as well as profundal sediments during the winter.

7.3.5. Carbon/Nitrogen ratio :

Carbon/Nitrogen (C/N) ratio of the sediment showed distinct seasonal and vertical distribution patterns in both the stations (Fig. 62) and varied between 5 and 35.

In deep water at station 1, the C/N ratio in the flocculent layer of the sediment was approximately 15 in mid July, it declined gradually to 5 in August and again increased gradually to 20 in early October. The C/N ratio

decreased slightly in mid October and again increased to the highest level (30) in late October to early November. It declined to 10 in mid November and similar levels remained till June, 1986.

In the first and second middle layer, C/N ratio remained around 10 during most of the time except in late July and from mid April to early May in the first middle layer and from December to mid February in the second middle layer when it increased to 15 and in October to early November when it reached to 20.

In the deep layer, C/N ratio was similar to the middle layer except in July when it reached to 30.

At station 2, C/N ratio in the flocculent layer remained around 15 in July, it declined to 10 in August and then increased gradually to the highest level (25) in late September to early October. The C/N ratio declined gradually to 10 in late November to early January, 1986 and again increased to 15 in February and March. It declined to 10 in early April and similar levels remained throughout the rest of the period.

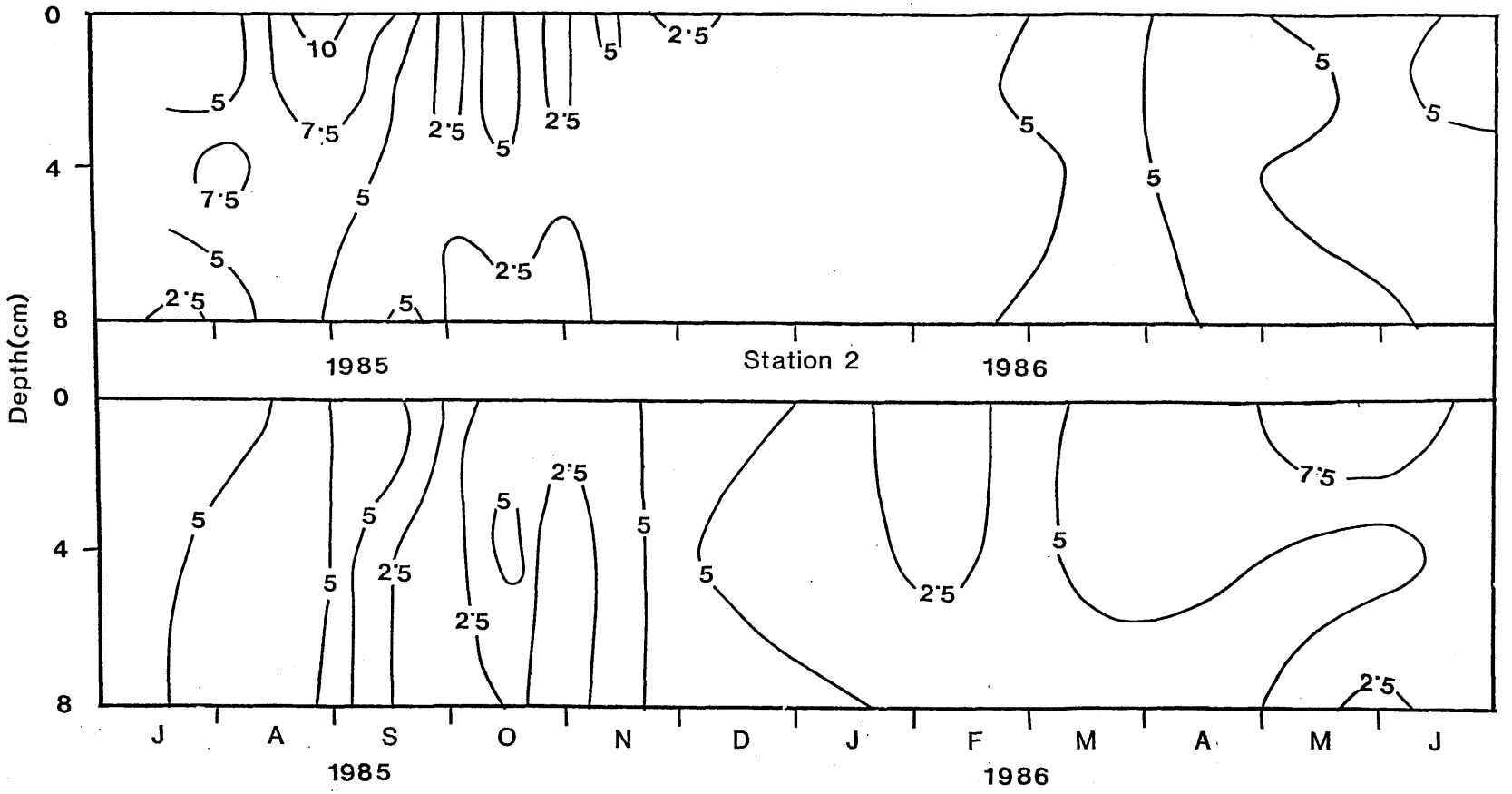
In the middle layer, C/N ratio was similar to the flocculent layer.

In the deep layer, C/N ratio was high (25) in late July and early August, it declined slightly (20) in mid August to early September and again increased to the highest level (35) in late September to early October. The C/N ratio declined gradually to 10 in early December and similar levels remained throughout the rest of the period of study.

Slack (1954) reported C/N ratios of Loch Lomond sediment varying from 5 to 44 which is very similar to the present study. Most of the values ranged from 10 - 20 which also agrees with the present study. Values between 10 and 20 is common in other oligotrophic lakes (e. g. Clay & Wilhm, 1979; Guppy & Happey - Wood, 1978; Pennington, 1973). The relative proportion of carbon with respect to nitrogen is used in agricultural research as indicating soil quality, has been employed in investigations of lake deposits with the object of determining the trophic state (Misra, 1938; Stangenberg, 1949). Stangenberg (1949) quoted several authors to show that C/N ratios of terrestrial plants are high (25 - 40) and of plankton and submerged phanerogams are low (5 - 10). In the present study on seston and sediment, C/N ratio ranged from 10 - 30 during most of the time and the highest levels (30 - 35) during late autumn indicates high content of allochthonous materials together with the influx of peat extracts from the drainage basin. In most lakes, C/N ratio generally falls as the organic content

Figure 63. Seasonal variations of Nitrogen/Phosphorus ratio in the sediment from July, 1985 to June, 1986.

Nitrogen/Phosphorus ratio in the sediment - Station 1



rises. Low organic matter and high C/N ratio indicating oligotrophy, and the converse eutrophy while high organic content and high C/N ratio denotes a high degree of dystrophy (Slack, 1954) which agrees with the present study. However, there are several reports where these generalizations do not fit (Misra, 1938 ; Stangenberg, 1949) and more data are required from many more lakes before it can be decided whether these factors are of real use in judging the trophic levels of lakes.

7.3.6. Nitrogen / Phosphorus (N/P) ratio :

Nitrogen / Phosphorus ratio of the sediment ranged from 2.5 to 10 showing slightly higher values during the summer months (Fig. 63).

In deep water at station 1, N/P ratio in the flocculent layer increased gradually from 5 in July to the highest level (10) during late August to early September when the sediment surface was completely deoxygenated (Fig. 5). After the autumn overturn, it declined rapidly to 2.5 in late September to early October. During October and November, N/P ratio showed irregular fluctuations ranging from 2.5 to 5. It increased gradually from 2.5 in December to 5 in late February, 1986 and similar levels remained during the rest of the period.

In the first middle layer (2cm from top), N/P ratio ranged from 2.5 to 7.5 and showed similar patterns of seasonal variations as was observed in the flocculent layer.

In the second middle layer (4cm from top), N/P ratio was the highest (7.5) in late July to mid August, it declined gradually to 5 in mid September and similar levels remained during the rest of the period of study.

In the deep layer (8cm from top), N/P ratio remained around 5 during most of the time except in late July and in October to early November when it declined to 2.5.

At station 2, N/P ratio ranged from 2.5 to 7.5 and vertical variation was observed only from mid March, 1986 to June. However, from July to early September N/P ratio remained around 5, it declined sharply to 2.5 in mid September and similar levels remained up to early November. The N/P ratio again increased to 5 in late November to early January, 1986, declined to 2.5 in late January to early February and again increased to 5 in early March.

From mid March, N/P ratio in the flocculent layer increased gradually from 5 to 7.5 during May and mid June. The N/P ratio in the middle layer (4 cm from top) remained

unchanged but in the deep layer (8cm from top) it declined gradually to 2.5 during May and early June.

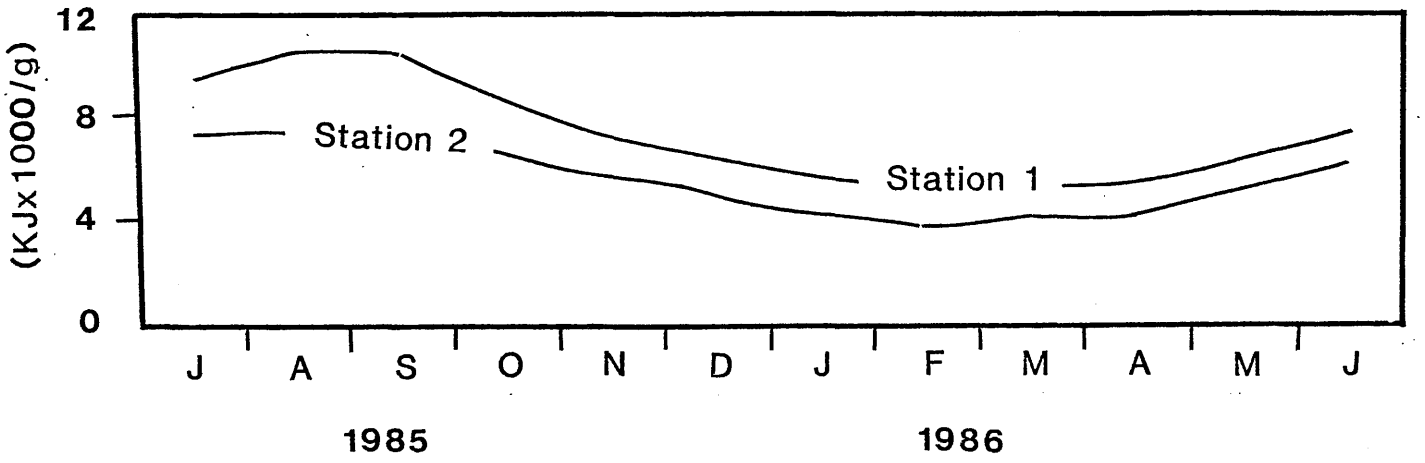
Slightly higher N/P ratio during late spring and summer than the rest of the period is related with high concentrations of nitrogen in the organic matter originating mainly from phytoplankton. The highest level during late summer was due to anaerobic decomposition of the sediment at a time when the sedimentation of seston was also high. The increase in N/P ratio in summer is presumably is a measure of the relative mobility of these two elements in the sediment. Nitrogen is much more soluble and therefore mobile than phosphorus even under anaerobic conditions. Although seston biomass (Fig. 44) was high during autumn and winter, N/P ratio was low which is due to low nitrigen content of organic matter originating mainly from the littoral macrophytes.

However, the variation of N/P ratio between the two stations was slight except in late July and August.

Golachowska (1984) studied lake sediments world wide and reported that N/P ratio varied from lake to lake irrespective of the type of the water body, its depth and climate.

Figure 64. Seasonal variations of energy content per gram dry weight of sediment from July, 1985 to June, 1986. Energy content is expressed in KJ x 1000/g.

Energy content of sediment



7.3.7. Sediment energetics :

7.3.7.1. Energy content per gram dry weight of sediment :

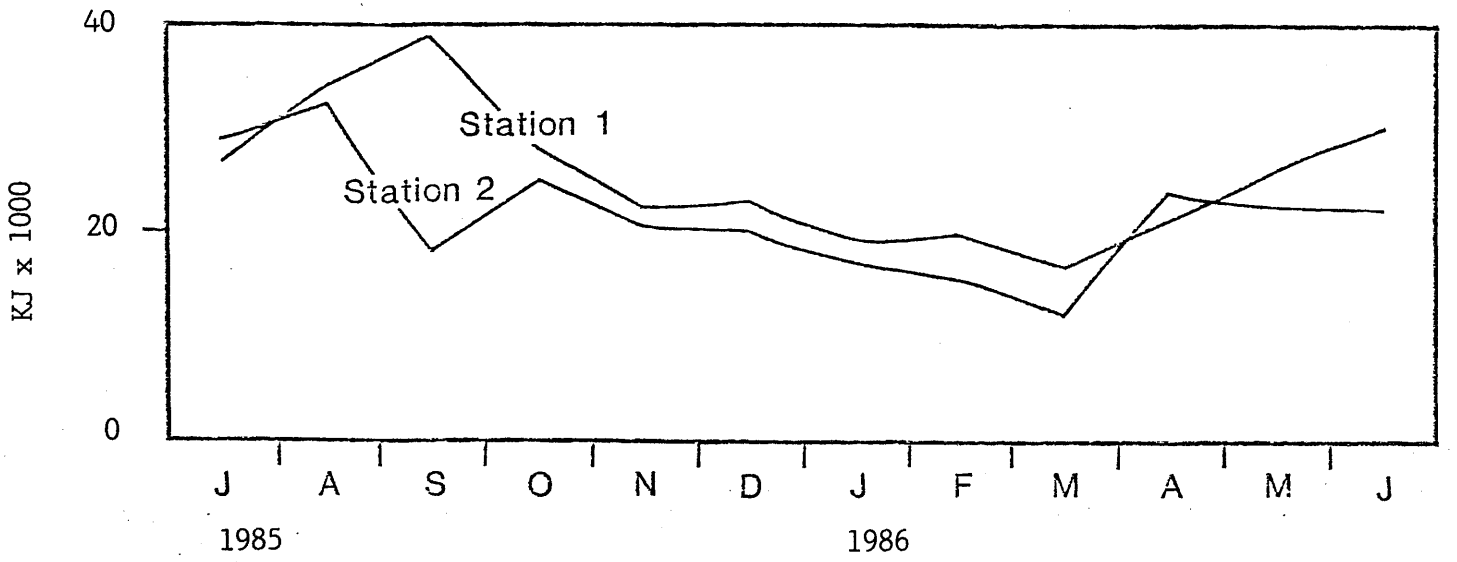
The energy content per gram dry weight of sediment was always higher at station 1 than at station 2 (Fig. 64) and showed close relationship with the energy content of seston collected from 9m depth (Fig. 52).

In deep water at station 1, the energy content of the sediment ranged from 5.2 X 1000 to 10.5 x 1000KJ/g. In the beginning of the study period, the energy content was high (9.4 x 1000KJ/g) in July, it increased to the highest level (10.5 x 1000KJ/g) in August and similar levels remained in September. It declined gradually from (8.6 x 1000KJ/g) October and reached to the lowest level (5.2 x 1000KJ/g) in March. It increased gradually from (5.5 x 1000KJ/g) April and reached to 7.5 x 1000KJ/g in June.

At station 2, the energy content of the sediment ranged from 3.8 x 1000 to 7.5 x 1000KJ/g. Although the seasonal pattern was similar, the levels were always slightly lower than station 1. The energy content of the sediment was at the highest level from July to September (7.2 x 1000 to 7.6 x 1000KJ/g), it declined gradually from (6.6 x 1000KJ/g) October and reached to the lowest level (3.8 x 1000KJ/g) in

Figure 65. Seasonal variations of energy content per gram ash free dry weight of sediment from July, 1985 to June, 1986. Energy content is expressed in KJ x 1000/g.

Energy content per gram ash free dry weight of sediment



February, 1986. It increased gradually from (4.2 x 1000KJ/g) March and reached to 6.3 x 1000KJ/g in June.

7.3.7.2. Energy content per gram ash free dry weight of sediment :

The energy content calculated on the basis of ash free dry weight of sediment (Fig. 65) also showed similar pattern of seasonal variation as was observed on dry weight basis (Fig. 64).

In deep water at station 1, the energy content of ash free dry weight of the sediment varied between 17.1 x 1000 and 39.3 x 1000KJ/g. The energy content was high in July (27.1 x 1000KJ/g), it declined sharply through August (34.1 x 1000KJ/g) and reached to the highest level (39.3 x 1000KJ/g) in September when the sediment surface was completely deoxygenated (Fig. 5). It declined sharply in October (28.4 x 1000KJ/g) and a gradual decline from November lead to the lowest level in March (17.1 x 1000KJ/g). The energy content increased gradually from April (22.8 x 1000KJ/g) and again reached to high level (30.0KJ/g) in June.

In shallow water at station 2, the energy content of ash free dry weight of the sediment varied between 12.0 x

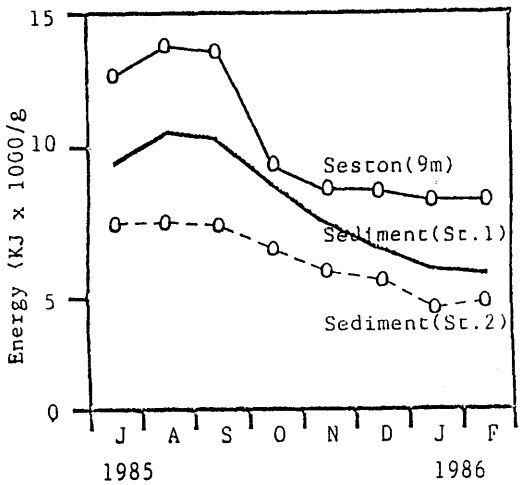
1000 and 33.1 x 1000KJ/g. The energy content was also high in July (29.8 x 1000KJ/g), it increased to the highest level in August (33.1 x 1000KJ/g) and then declined sharply in September (18.3 x 1000KJ/g). The energy content again increased sharply in October (25.1 x 1000KJ/g) and then declined gradually from November (21.3 x 1000KJ/g) and reached to the lowest level in March (12.0 x 1000KJ/g). It increased sharply in April (24.3 x 1000KJ/g) and then declined slightly in May (22.8 x 1000KJ/g) and similar levels remained in June (22.7 x 1000KJ/g).

Comparatively higher levels of energy in the sediment during the whole summer than the rest of the period in both the stations at a time when the sediment received high energy content seston (Fig. 52) mainly from the death and decomposition of phytoplankton. Salmi (1954) recorded a striking positive correlation between energy content and the degree of decomposition of sediment in two Finnish lakes. Gorham & Sanger (1967) evaluated the role of source material in the energy content of sediment and concluded that sediment receiving more algal material contain higher energy than those receiving organic matter from aquatic macrophytes. The highest energy content of the sediment at station 1 during August and September when the hypolimnion was completely deoxygenated (Fig. 5) could be related with anaerobic decay of sediment organic matter. Gorham & Sanger

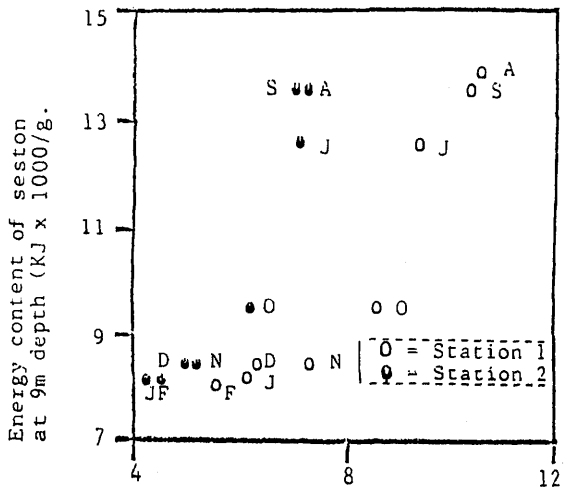
(1967) reported that organic matter of the anaerobic lake mud is highly comminuted and decomposed and this condition may be partly responsible for its high energy content. Shallow parts of the lake such as at station 2, exposed to wind, are characterized by the continuous resuspension of organic matter which becomes oxidized with a resulting loss of energy (Jonasson, 1979). Due to continuous resuspension of organic matter and the preferential accumulation of mineral particles, the proportion of mineral particles in the sediment will be higher than organic matter.

Hence loose, low energy content material covered the bottom and lowered the energy content of the sediment. The low energy content of the sediment from December to March, 1986 could be related with low production of phytoplankton (Fig. 23) and low energy content of organic seston originated mainly from the death and decomposition of aquatic macrophytes and allochthonous organic and inorganic materials. Comparatively lower energy content of the sediment at station 2 than station 1 during the whole period of study could be related with particle size (not determined in the present study) of sedimenting organic matter. Larger particles of organic matter settle first and smaller particles remain in suspension until reaching the quiter, deeper waters (Clay & Wilhm, 1979). Frink (1969) established good correlation between particle size and water depth.

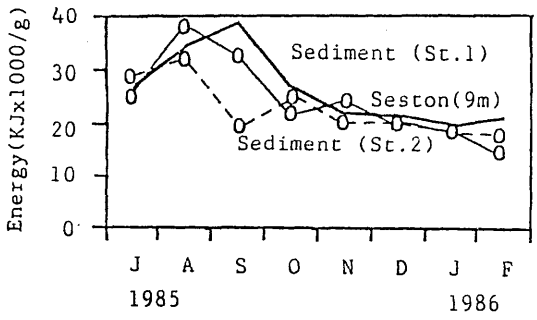
Figure 70 (A,B,C,D). Relationship between energy content of seston and sediment.



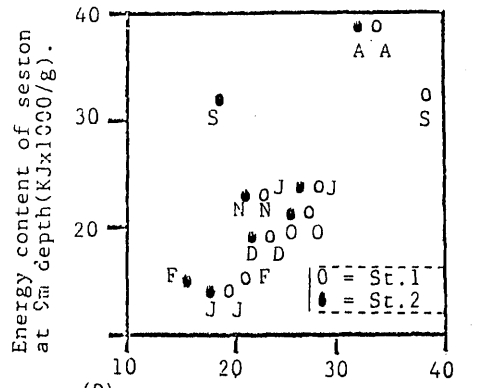
(A) Seasonal variations of energy content of seston(9m depth) and sediment (Dry weight).



(B) Energy content of sediment (Dry weight) (KJ x 1000/g.



(C) Seasonal variations of energy content of seston(9m depth) and sediment (ash free dry weight).



(D) Energy content of sediment (ash free dry wt.) KJx1000/g.

Gorham & Sanger (1967) graded the sediment samples according to particle size by sieveing dried samples and found that the energy content increased directly with decreasing particle size of the sediment. Comparatively higher energy content of the sediment in deeper part than in the shallower part of the same lake have been reported by several workers (e.g. Gorham & Sanger, 1967; Lastein, 1976; Jonasson, 1979).

Relationship between seston and sediment energetics :

The precise relationship between seston and sediment energetics is difficult to establish although seston production over a period of time, per unit lake surface could be assessed using a trap, organic matter received by the sediment over that period and area could not be seperated from the exhisting organic content of the sediment. Thus the only basis for comparison is the energy content per gram dry weight of both seston and sediment. In considering the energy content of seston and sediment on this basis, a problem still remains because the sediment contains much higher proportions of minerals than seston as it receives not only seston but also minerals from allochthonous sources including drift from the shore which do not come through seston. To overcome such a problem, the energy content of sediment is also compared with seston energetics on an ash free dry weight basis.

Although seston samples were collected from 1m and 9m depth, 1m samples were excluded from this comparison because of periphytic algal growth inside the seston tubes and also the degree of decomposition of organic matter between the two depths due to delay in sedimentation process.

The comparison of sediment energetics from deep (St.1) and shallow (St.2) water with seston is still problematic because deep water sediment receives more decomposed seston mainly from algal material which passes through lower to deeper water column and shallow water sediment receives comparatively less decomposed organic matter with a higher proportion probably coming from the dead and decomposed aquatic macrophytes and leaf litter from the shore. During the periods of thermal stratification especially from July to September, the deep water sediment surface is deoxygenated whereas shallow water sediment surface always remain well oxygenated and the effect of aerobic and anaerobic decomposition on sediment is apparent.

Comparatively higher proportions of minerals in the shallow water sediment (washed away from the shore) than in deep water sediment is also another important factor. However considering all these problems and assuming that the sediment in both shallow and deep water receive similar sorts of seston, a comparison of the energy content on seston and sediment (both dry wt. and ash free dry wt. basis) is made by presenting data on their seasonal variations in the same figure (Fig.70) and also by plotting the energy content of sediment against seston.

The highest energy content of seston and comparatively higher energy content of sediment (on dry wt. basis) at station 1 than station 2, during the whole period of study was probably due to the lower proportion of minerals in seston and sediment at station 1. During the periods of thermal stratification, the energy content of seston and deep water sediment (on an ash free dry wt. basis) were also higher than the shallow water sediment. The energy content of seston and sediment at station 1 did not differ greatly and even the energy content of sediment were slightly higher than seston in September, October, December, 1985 and February, 1986. As carbohydrate (weight for weight) has a higher calorific value than protein and if the protein content in the organic matter of the sediment is converted to carbohydrate due to bacterial decomposition, the energy values of the sediment during this period could increase with no change in the amount of organic matter.

When the energy content of sediment (on both dry and ash free dry wt. basis) from both deep and shallow water were plotted against the energy content of seston, it was observed that the energy content of sediment at station 1 increased directly with seston but at station 2, it increased less rapidly with seston energetics.

The sharp increase of energy content of seston and sediment at station 1 during July and August and high level in September was probably due to the effect of a combination of deoxygenation of sediment surface at a time when the supply of seston was high due to summer algal bloom earlier in June and July. The lowest level of energy content of sediment at station 2, during the same period was probably due to continuous mixing and differential resuspension of organic matter from sediment at a time when the sediment surface probably received most of the organic matter from dead and decomposed aquatic macrophytes and other allochthonous sources including leaf litter from the shore.

CHAPTER - 8.

BENTHOS

8.1. Introduction :

Quantitative knowledge of benthos are considerably less than plankton especially in Dubh Lochan. Benthic environments and communities are more difficult to study quantitatively. In addition, the processing of benthic samples are time consuming. These problems have to some extent limited the advancement of the Knowledge of benthos (Kajak et al., 1980).

Benthic organisms may play a significant role in functioning lacustrine ecosystem. Many attempts have been made to classify lakes on the basis of their benthic fauna (Brinkhurst, 1974). Benthos are very important sediment processors, causing mixing in the layers in which they live and control bacterial populations by continuous grazing. The role of benthos in the exchange of chemicals between mud and water by stirring the mud and pumping water through their burrows must be significant (Kajak et al., 1980) although little work has been done on the quantitative aspects (Tessenow, 1964; 1972). Tessenow (1964) indicated that Chironomids cause a 4 fold increase in the rate of

silica release from the sediments. Davies et al., (1975) showed that Tubificids play a minor role in phosporus release and may actually enhance phosphorus deposition. Gallepp (1979) reported that Chironomids enhance phosphorus release and where abundant in the aerobic region of lake sediments, their activities may be expected to result in a significant source of phosphorus to the epilimnetic region.

They are also important in the energy transfer process in lacustrine ecosystems. Benthic filter feeders may be very important in removing the seston from the water and depositing it at the bottom (Stanczykowska, 1968; Lvova-kachanova, 1971). The biomass and production of lacustrine benthos have been discussed in relation to primary production by Brylinski (1980), Davies (1980) and Morgan (1980). Although Jonasson (1972) demonstrated a clear dependance of Chironomid secondary production on the primary production in Lake Esrom, the efficiency of energy transfer from primary production to the secondary production of benthos varies widely among different lakes (Morgan, 1980). The mode of life of benthos greatly differ between the deep, stratified, deoxygenated zone and the shallow well oxygenated zone even in the same lake. The energy transfer process from phytoplankton to benthos through seston and sediment is quite complex and sometimes controlled by the

environmental factors especially temperature and dissolved oxygen (Iwakuma et al., 1984).

8.2 Materials and Methods :

Sediment samples were collected once a month using an Eckman grab (sampling area = 15.25cm^2) from station 1 and station 2, for the collection of benthic organisms. The samples were collected from 10 to 15m radius of each station so that the seston samples are not affected. In an attempt to determine the number of grab samples required for a representation of the benthic organisms, 10 samples were collected from each station. The number of benthos were plotted against the number of samples and it was found that 5 samples were enough to represent the benthic community. The average counts of 5 samples were, therefore, considered for each station on each sampling date for routine investigation. All the samples at each station were collected separately in plastic buckets and carried to the laboaratory. Each sample was placed in a cylindrical sieve (mesh size = 0.5mm^2) and swirled in tap water until the run off water was clear. The remaining material was transferred into a sorting tray. The benthic organisms were sorted out immediately when they were alive because of greater sorting efficiency. Each species of benthos was collected in separate vials. They were identified according to Cranston

(1982) and Macan (1959 ; 1969). The number of individuals in each species were noted and then they were dried in an oven at 100°C for 2 hours to get a constant dry weight. The energy content of the benthos was calculated applying a conversion factor of 24543.12KJ/g dry weight of benthos which was given for Chironomus plumosus by Cummins & Wuycheck (1971). Chironomus plumosus was the only species of benthos observed at station 1. Although 6 species of benthos were observed at station 2, Chironomid larvae dominated during the whole period of study. The energy content of benthos should, therefore, be considered as an approximation.

8.3. Results and Discussion :

8.3.1. Species composition :

The species composition of benthos differed greatly betwen station 1 and station 2.

In deep water at station 1, only 1 species of benthos, Chironomus plumosus was observed during the whole period of study. Another species of benthos, Chaoborus flavicans was also observed but it was not included in the present study because the species is normally benthic in daytime and planktonic at night and since it feeds mainly on plankton

Table 8. Species composition and abundance of benthos at station 2 from March, 1985 to February, 1986 in Dubh Lochan.

Months	Number of benthos/m^2 lake bottom at station 2					
	Chironomus plumosus	*Chironomus* sp.	*Procladius* sp.	*Sialis lutaria*	*Sigara* sp.	*Pisidium* sp.
March, 1985	--	178	104	45	--	89
April	--	133	89	45	--	148
May	--	208	459	45	--	311
June	45	311	445	45	--	311
July	45	193	415	--	--	371
August	45	252	297	45	--	312
September	45	104	75	45	--	133
October	--	59	59	45	--	--
November	--	--	--	59	--	--
December	--	--	--	45	45	--
January, 1986	--	--	--	45	45	--
February	--	--	--	45	--	--

(Goldspink & Scott, 1971), must be considered as far as energy interactions are concerned, as being planktonic.

In shallow water at station 2, six species of benthos, Chironomus plumosus, Chironomus sp., Procladius sp., Pisidium sp., Sialis lutaria and Sigara sp., were recorded during the period of study (Table 8).

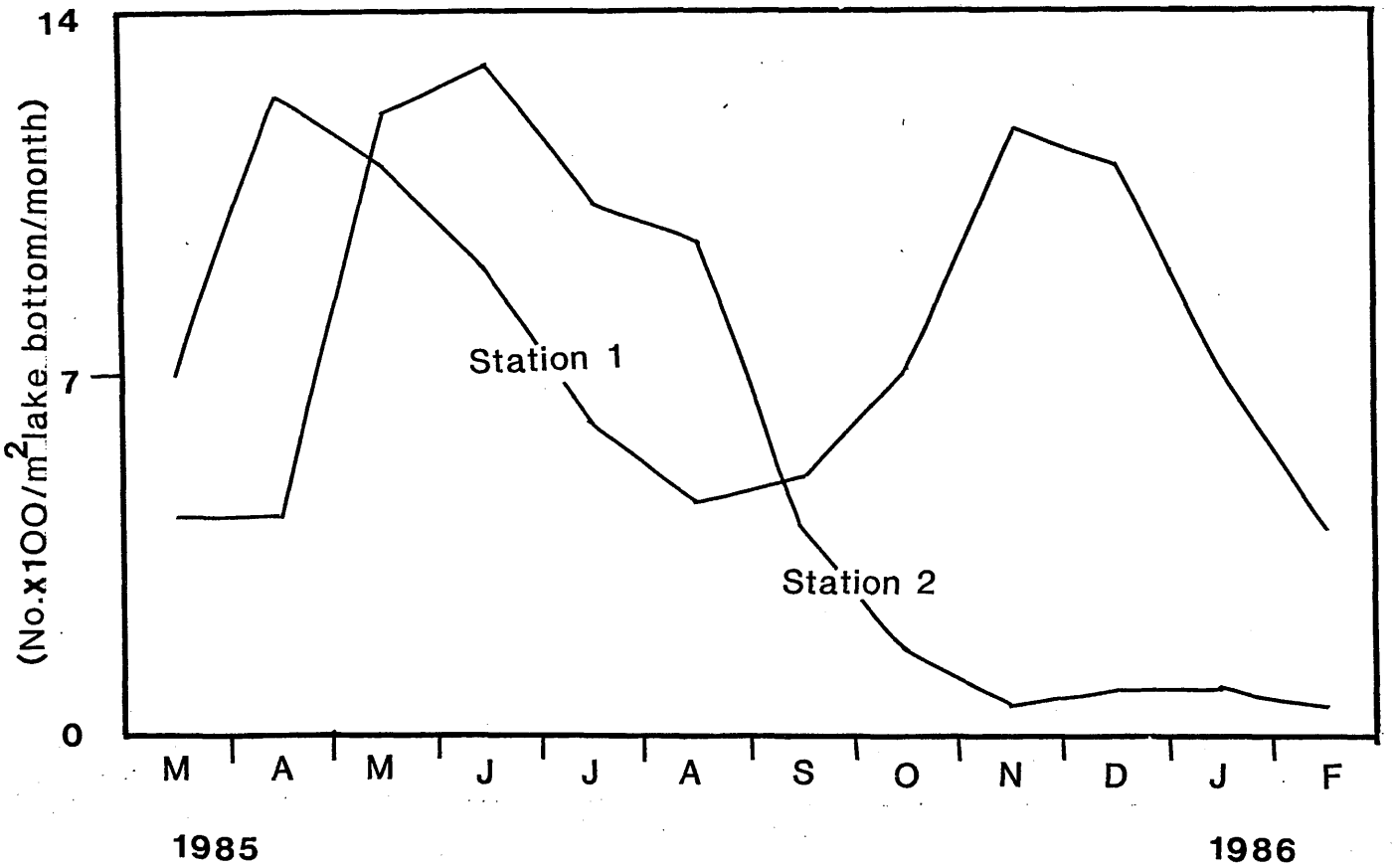
The profundal benthos living in a structurally less complex habitat, has reduced the diversity which is probably due to the deoxygenation to which they are subjected and may have limited the diversity even when the oxygen supply at the bottom is abundant. Moss (1982) reported that many profundal communities are dominated by Chironomid larvae and during the summer stagnation when the sediment surface is covered by anaerobic water, the Chironomid fauna is even reduced to one or two species like Chironomus plumosus. Littoral animals cannot survive the low or even zero oxygen concentration that C. plumosus can. The respiratory rates of most of the organisms fall progressively with declining oxygen concentrations of the water while C. plumosus remains high and constant over a wide range of oxygen concentrations. Mason (1981) reported that the haemoglobin in the blood of Chironomids acts as a carrier mainly when the oxygen tension of the water is low, at a time when the amount of oxygen required by the animals can not be supplied

by physical solution. The mechanism of their survival in completely deoxygenated condition is still not clear, although it is widely believed that they store enough oxygen in their haemoglobin to maintain their actiivities (Moss, 1982). He also reported that the haemoglobin they contain can only store enough oxygen to maintain their activities for a very short time, so it is highly unlikely that this oxygen is enough during prolonged deoxygenation.

Although station 2 is comparatively shallower (5m deep) than station 1 (10m deep), it is still below the euphotic depth. The benthic community at station 2 is more diverse than station 1 but it is much less than the littoral community where 30 species of benthos were recorded (Table 4). The littoral area of Dubh lochan is generally covered with dense beds of aquatic macrophytes from late spring to early autumn. Moss (1982) reported that submerged weed beds have a rich invertebrate fauna and provide cover from predators. Below the euphotic depth, apparently bare sediment usually harbours a community of invertebrates, less diverse than that of the weed beds and is often dominated by Chironomid larvae.

Figure 66. Seasonal variations of benthos biomass from March, 1985 to February, 1986. Benthos biomass is expressed as number/m^2 lake bottom/month.

Benthos biomass



8.3.2. Seasonal abundance of individual species :

Chironomus plumosus :

The seasonal abundance of Chironomus plumosus varied greatly between the two stations.

In deep water at station 1, total number of C. plumosus ranged from 400 to 1240/m^2lake bottom/month and showed two distinct seasonal peaks, one in April and the other in November (Fig. 66). It increased rapidly from March (700/m^2 lake bottom/month) and reached to the highest level in April (1240/m^2 lake bottom/month). The populations declined gradually from May and reached to a very low level during August (450/m^2 lake bottom/month) and September (500/m^2 lake bottom/month). It increased slightly in October and a rapid increase in November (1170/m^2 lake bottom/month) resulted in its second peak. The populations declined slightly in December with a rapid decrease during January, 1986 resulted in its lowest level in February (400/m^2 lake bottom/month).

In shallow water at station 2, C. plumosus was present in small numbers (45 to 59/m^2 lake bottom/month) from June to September (Table 8).

The highest numbers of C. plumosus during April and

high numbers in November at station 1 could be related to their reproduction during the periods of optimum environmental conditions. The highest peak during April was just prior to phytoplankton bloom (Fig. 23) and the peak in November was just after the autumn overturn with high populations of diatoms (Figs. 30 - 34). Morgan (1980) reported that C. plumosus has 1 to 3 generations per year in temperate lakes depending on such ecological factors as temperature and food supply. In Dubh Lochan, it seems there were two generations, one in late spring and the other in late autumn.

Low numbers during the early summer could be due to the emergence (not determined in the present study) of C. plumosus as they become adult and leave the sediment to be terrestrial. The low numbers during August and September could be due to the effect of deoxygenation of the sediment. Very low levels during January, 1986 and February could be related to low temperature as well as the supply of low energy content detritus (Fig. 52).

The presence of small numbers of C. plumosus at station 2 (Table 8) during the periods of thermal stratification (June to September) could be due to migration from the deep water sediment.

Chironomus sp. :

Chironomus sp. was present from March to October at station 2 only. The population was high in March (178/m^2 lake bottom/month), declined slightly in April (133/m^2 lake bottom/month) and a gradual increase from May lead to the highest level in June (311/m^2 lake bottom/month). The populations declined sharply in July (193/m^2 lake bottom/month) and again increased sharply in August (252/m^2 lake bottom/month). It declined sharply through September and October (59/m^2 lake bottom/month) and disappeared in November and the species was absent till February, 1986.

Procladius sp. :

Procladius sp. was recorded from March to October at station 2 only (Table 8). It ranged from 59 to 459 individuals/m^2 lake bottom/month. The populations remained low during March and April (89 to 104/m^2 lake bottom/month), it incresed to the highest level in June (459/m^2 lake bottom/month) and similar levels remained up to July. It declined sharply in August (297/m^2 lake bottom/month) and a sharp decline through September resulted in its lowest level in October (59/m^2 lake bottom/month) and disappeared by November. The species was absent from November to February, 1986.

The sediment surface at station 2 was always well oxygenated and never dropped below 55% saturation (Fig. 6).

The rapid increase of the numbers of both Chironomus sp., and Procladius sp., in May could be related to their reproduction and high levels during the whole summer seems to be related with the supply of high energy content algal detritus (Fig. 52) during favourable environmental conditions especially temperature (Fig. 4). The sharp decline in numbers of both the species during September and October and their absence from November to February, 1986 could be due to their emergence as they become adult and leave the sediment to be terrestrial.

Sialis lutaria :

Sialis lutaria was present throughout the year except in July at station 2 only (Table 8), but their population remained very low (45 to 59/m^2 lake bottom/month).

Sigara sp. :

Sigara sp., was present only at station 2 (Table 8) in December and January, 1986 and their population also remained very low (45/m^2 lake bottom/month). The species

could have migrated in from littoral sites during very cold weather when the littoral area was frozen.

Pisidium sp. :

Pisidium sp., a tiny pea shell cockle was observed from March to September at station 2 only and ranged from 89 to 371 individuals/m^2 lake bottom/month (Table 8). The population increased gradually from March (89/m^2 lake bottom/month) and reached to the highest level in July (371/m^2 lake bottom/month). It declined rapidly in September (133/m^2 lake bottom/month) and disappeared by October. The species was absent from October to February, 1986.

The rapid increase in total numbers of Pisidium from April and high levels from May to August coincide with high production of phytoplankton (Fig. 23) at a time of optimum environmental conditions. The absence of the species from October to February, 1986 could be due to both unfavourable environmental conditions specially very low winter temperature and short supply of food.

8.3.3. Benthos biomass :

Benthos biomass expressed as total numbers/m^2 lake bottom/month varied greatly between the two stations.

In deep water at station 1, Chironomus plumosus was the only species of benthos observed during the present study and the seasonal pattern has already been described in the previous section (8.3.2). The seasonal variations of biomass of a single species is, therefore, compared with the total number of benthos observed at station 2.

In shallow water at station 2, the seasonal variation of total number of benthos was very different from station 1. It ranged from 50 to 1290/m^2 lake bottom/month and showed a single summer maximum. Total number of benthos was low (420/m^2 lake bottom /month) during March and April, it increased very rapidly (1200/m^2 lake bottom /month) in May and reached to the highest level (1290/m^2 lake bottom /month) in June. Total number of benthos declined gradually during July (1030/m^2 lake bottom/month) and August (950/m^2 lake bottom/month) and a rapid decline during September and October lead to the lowest level (60/m^2 lake bottom/month) in November and similar levels remained throughout the rest of the period of study.

Figure 67. Seasonal variations of benthos biomass from March, 1985 to February, 1986. Benthos biomass is expressed as dry weight in g/m^2lake bottom/month.

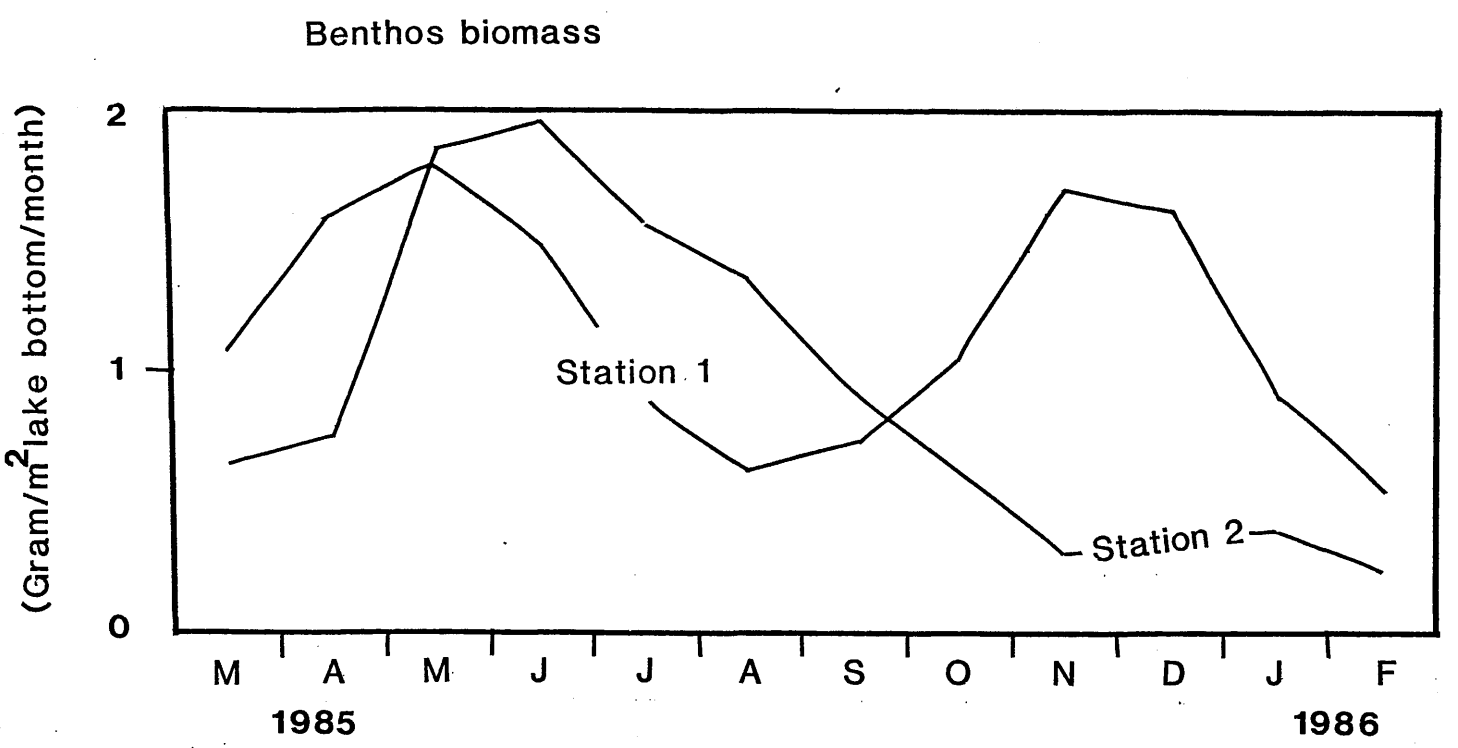
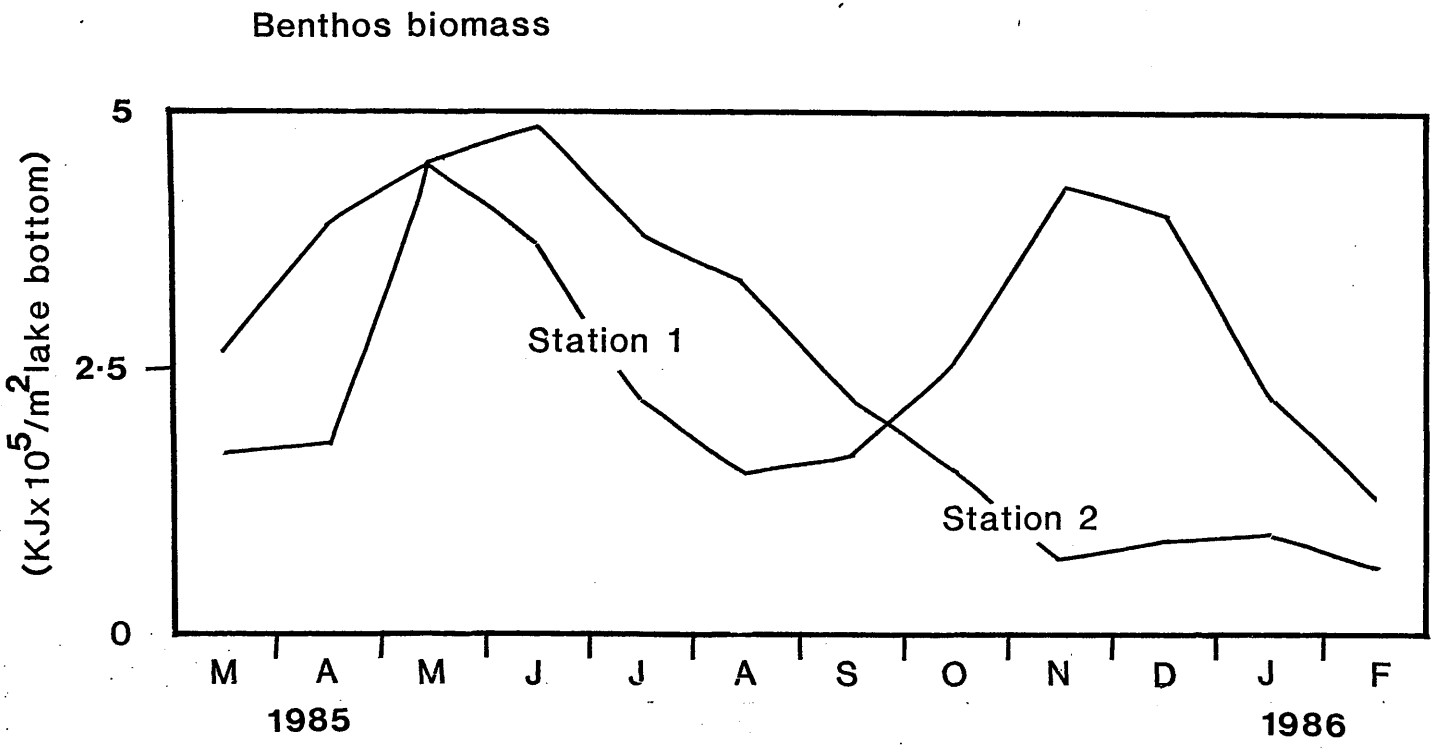

Benthos biomass
(Gram/m2lake bottom/month)
2
1
0
Station 1
Station 2
M
A
M
J
J
A
S
O
N
D
J
F
1985
1986

Figure 68. Seasonal variations of benthos biomass from March, 1985 to February, 1986. Benthos biomass is expressed in KJ x $10^5/m^2$ lake bottom/month.


Benthos biomass
5
2·5
0
(KJx10^5/m^{2}lake bottom)
Station 1
Station 2
M
A
M
J
J
A
S
O
N
D
J
F
1985
1986

Benthos biomass estimated by dry weight (110°C for 2 hours) showed similar patterns of seasonal variations (Fig. 67) as was observed in total numbers (Fig. 66). It also showed two peaks at station 1, one in spring and the other in late autumn and a single summer peak at station 2.

Benthos biomass ranged from 0.54g/m^2 lake bottom/month in February, 1986 to 1.8g/m^2 lake bottom/month in May, 1985 in deep water at station 1 and in shallow water at station 2, it ranged from 0.24g/m^2 lake bottom/month in February, 1986 to 1.96g/m^2 lake bottom/month in May, 1985.

Benthos biomass calculated in terms of energy, ranged from 0.14725 x 10^5KJ/m^2 lake bottom/month in August to 0.4477 X 10^5KJ/m^2 lake bottom/month in May in deep water at station 1 and from 0.06135 x 10^5KJ/m^2 lake bottom/month in February, 1986 to 0.47859 x 10^5KJ/m^2 lake bottom/month in June, 1986 in shallow water at station 2 (Fig. 68) showing similar patterns of seasonal variations as was observed in total numbers (Fig. 66) and dry weight (Fig. 67) during the whole period of study.

In deep water at station 1, the seasonal peaks of benthos biomass neither correlates with phytoplankton biomass nor primary production. During the periods of high phytoplankton biomass and primary production in summer

months (June to August) benthos biomass declined nearly to the lowest level and when benthos biomass reached to the peaks during spring and late autumn, both phytoplankton biomass and primary production was very low. However, benthos biomass showed close relationship with diatom production (Figs. 30-34) although diatoms constituted a tiny fraction of phytoplankton biomass. Morgan (1980) reported that in profundal of stratified temperate lakes, maximum in benthos biomass occur mostly in spring (April & May) and in autumn (October) while phytoplankton and primary production reach maximum during summer (Moss, 1980). Iwakuma et al.,(1984) observed that fluctuations in the secondary production of Chironomids was independent of fluctuations in the phytoplankton abundance. Environmental factors such as water temperature and dissolved oxygen could be responsible in controlling their production. Although Jonasson (1972) has demonstrated a clear dependance of Chironomid secondary production on the primary production in lake Esrom, the efficiency of energy transfer from the primary production to the secondary production of benthos varies widely among different lakes depending on the trophic status and mode of life of the benthos (Morgan, 1980). Benthos biomass showed close relationship with seston biomass from March to June and October to February, 1986. During thermal stratification and deoxygenated sediment surface from July to September, benthos biomass declined to a very low level

although seston biomass was very high in August. During the periods of high benthos production in spring and autumn, seston originated mainly from aquatic macrophytes and in summer months when benthos production was low, seston originated mainly from phytoplankton. Johannsson & Beaver (1983) reported that the contribution of algae as a food source to the energetics of Chironomus plumosus was small and reached a maximum of 15-34% in August and September but during the rest of the year it varied between 2 and 8%. It was suggested that detritus with its associated microorganisms may supply the remainder. Moss (1982) indicated that bacteria and other microorganisms grown in fine sedimenting organic matter play an important role in the diet of Chironomid larvae while organic matter alone can not support their growth.

Benthos biomass at station 1 comprised only C. plumosus. In the profundal of temperate lakes it has generally 1-3 generations per year (Morgan, 1980) which is governed by body size and such ecological factors as temperature, dissolved oxygen and food supply (Morgan, 1980). In Dubh Lochan, it seems that it had 2 generations, one in April and the other in November. High production of benthos in spring and autumn seems to be related with optimum temperature at a time when sediment receives high quantities of organic seston. Low production of benthos

from July to September at a time when seston production was high seems to be due to the deoxygenation of sediment surface.

At station 2, benthos biomass clearly follows phytoplankton biomass and primary production (recorded at station 1 only). Maximum benthos production in June and high level from May to August could be related to high temperature and well oxygenated sediment surface at a time when sediment receives high energy content organic seston mainly from the death of phytoplankton. The highest production of benthos (June) at station 2 did not differ greatly from station 1 (April). Although station 2 is comparatively shallower than station 1, it is still beyond euphotic depth and the sediment receives organic matter mainly from the sedimenting seston.

CHAPTER - 9.

ENERGY FLOW

9.1. General :

The energetics and biomass of individual compartments as well as seasonal variation and the factors which influence them have been dealt with seperately in Chapter 4 (phytoplankton), Chapter 5 (zooplankton), Chapter 6 (seston), Chapter 7 (sediment) and Chapter 8 (benthos). In this chapter, the data on energy flow from primary production of phytoplankton to various compartments have been compiled (Table 9) and discussed on both monthly and annual bases.

Primary production measurements were made over a 4 hour period, these data were then converted to monthly values, thus enabling direct comparison with all other calorific values which were determined on a monthly basis. Thus the hourly average for the month was multiplied by the total number of daylight hours for that month to obtain the monthly primary production. Cloud cover was not accounted for, this may represent a minor source of error.

Table 9. Energy flow from phytoplankton to benthos in Dubh Lochan.

Months	Phytoplankton		*Zooplankton		Seston						Sediment		Benthos			
	Primary production ($KJ \times 10^3/m^2/month$)		Biomass$_c$ ($KJ \times 10^3/m^2/month$)	Efficiency (percentage)	Energy content ($KJ \times 10^3/g$)		Biomass ($KJ \times 10^5/m^2/month$)		Efficiency (percentage)		Energy content ($KJ \times 10^3/g$ dry wt.		Biomass$_c$ ($KJ \times 10^5/m^2/month$		Efficiency (percentage)	
	1984-1985	1985-1986			1m	9m	1m	9m	1m	9m	Station 1	Station 2	Station 1	Station 2	Station 1	Station 2
February	0.06321	0.05698	0.00336	5.89	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -
March	0.56720	0.34244	0.01974	5.76	0.08442	0.07350	2.36376	4.48350	>590.30	>1209.30	- - -	- - -	0.26997	0.17180	78.83	50.16
April	1.61752	0.55377	0.02856	5.15	0.10122	0.09030	3.03660	6.05010	>448.40	>992.50	- - -	- - -	0.39268	0.18407	70.91	33.24
May	6.74031	13.76134	0.20034	1.45	0.12390	0.08400	4.21260	4.62000	30.80	33.57	- - -	- - -	0.44177	0.45404	3.21	3.297
June	22.73282	14.51388	0.09996	0.69	0.14910	0.10500	7.75320	2.62500	53.42	15.58	- - -	- - -	0.36814	0.47859	2.54	3.29
July	24.49695	15.28684	0.08610	0.56	0.14700	0.12600	8.96700	3.78000	58.66	24.85	0.09450	0.07150	0.22088	0.38041	1.44	2.49
August	13.22500	4.28878	0.13020	3.04	0.12600	0.13986	10.71000	9.37062	>149.72	>118.49	0.10542	0.07202	0.14725	0.33133	3.43	7.73
September	8.64605	7.92692	0.04620	0.58	0.10500	0.13650	2.83500	2.86650	35.76	36.16	0.10458	0.07104	0.17180	0.22088	2.16	2.79
October	11.26255	12.31692	0.01050	0.08	0.10164	0.09450	3.45576	2.45700	28.05	19.94	0.08610	0.06242	0.25770	0.14725	2.09	1.19
November	2.00750	2.91740	0.00336	0.11	0.09450	0.08442	3.30750	5.82498	>13.37	>99.66	0.07350	0.05212	0.41723	0.07362	14.30	2.52
December	0.37500	0.26654	0.00168	0.63	0.09030	0.08400	2.25750	4.36800	>199.09	>1538.77	0.06342	0.05082	0.39268	0.08590	147.32	32.22
January	0.05000	0.04014	0.00168	4.18	0.07350	0.08190	1.47000	4.50450	>142.98	>446.43	0.05120	0.04112	0.22088	0.09326	550.27	232.33
February	- - -	- - -	- - -	- - -	0.07140	0.08022	1.78500	4.73298	- - -	- - -	0.05460	0.03880	0.13498	0.06135	- - -	- - -
March	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	0.05250	0.04158	- - -	- - -	- - -	- - -
April	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	0.05502	0.04242	- - -	- - -	- - -	- - -
May	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	0.06258	0.05250	- - -	- - -	- - -	- - -
June	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	- - -	0.07560	0.06258	- - -	- - -	- - -	- - -
Yearly total/92.353 average		72.272	0.63168	0.87	0.105665	0.09835	52.15	55.68	72.16	77.04	0.07325	0.05491	3.43596	2.68250	74.22	33.75

* Based on Klarer (1978)

The energetics of zooplankton was not determined in the present study and all the values were calculated from (Klarer, 1978).

9.2. Primary production - Zooplankton biomass :

Primary production in February and March was very low which was also reflected by low zooplankton biomass. With increasing primary production in April (0.55 x 10^5KJ/m^2/month) and a very rapid rise in May (13.76 x 10^5KJ/m^2/month), zooplankton biomass reached to the highest level (0.2 x 10^5KJ/m^2/month). Primary production increased slightly in June and reached to the highest level in July (15.28 x 10^5KJ/m^2/month) but zooplankton biomass declined gradually to 0.086 x 10^5KJ/m^2/month. Primary production declined rapidly in August (4.28 x 10^5KJ/m^2/month) but zooplankton biomass increased to 0.13 x 10^5KJ/m^2/month. Although primary production increased in September and reached to a second peak in October (12.31 x 10^5KJ/m^2/month), zooplankton biomass declined to 0.010 x 10^5KJ/m^2/month. As production level declined sharply in November and reached to the lowest level (0.04 x 10^5KJ/m^2/month) in January, 1986, zooplankton biomass also declined to the lowest level (0.0016 x 10^5KJ/m^2/month).

The efficiency of energy transformation from phytoplankton to zooplankton showed great seasonal variations. It ranged from 0.08 to 5.89%. The highest level was in February and slightly lower levels remained up to April (5.15%) when the primary production was very low. The efficiency of energy transfer declined sharply in May(1.45%) with rapid increase in primary production. It declined gradually from June (0.69%) and reached to the lowest level (0.08%) in October except in August when it increased to 3.4%. The efficiency of energy transfer increased slightly in November and December (0.63%) and again reached to high level (4.16%) in January, 1986. On an annual basis, energy transformation from phytoplankton to zooplankton was only 0.87%.

On an annual basis, Klarer (1978) reported 3.7% energy transformation from phytoplankton to zooplankton in Dubh Lochan which is approximately 4 times higher than the present study. This difference could be mainly due to the change in the species composition of both phytoplankton and zooplankton.

Many workers used a ratio of zooplankton biomass to primary production as a measure of utilization of phytoplankton by zooplankton (e.g. Slobodkin, 1960; Schindler, 1972; Winberg et al., 1972). Klarer (1978)

compared the energy transformation from phytoplankton to zooplankton of 13 lakes of various trophic status from different parts of the world and the efficiencies varied from 1.6% in an eutrophic lake (Severson lake in U.S.A.) to 49% in an oligotrophic lake in Finland (Paajarvi lake). Jonasson (1979) compared the energy transformation from phytoplankton to zooplankton of 11 northern temperate lakes and the ratio calculated varied from 0.03 to 13.7%. The only Scottish lake included in the comparison was Loch Leven where 2.6% of the energy was transformed from phytoplankton to zooplankton. Brylinski (1980) reviewed the efficiency of energy transfer from phytoplankton to zooplankton of a group of lakes and found a mean value of 7.1%, ranging from 0.10 to 27.4%. Most of the other reports suggest an energy transformation of 10 to 15% from phytoplankton to zooplankton in oligotrophic lakes (Hillbricht - Ilkowska, 1972; Schindler, 1972; Pederson et at., 1976).

The efficiency of energy transfer from phytoplankton to zooplankton varies widely among different lakes. Significant variations could also be observed in the same lake in different seasons and in different years. Several biotic and abiotic factors could be responsible for such variations in natural ecosystems (Brylinski, 1980). Primary production may increase as a result of successful growth of any algal species which may not be suitable food for zooplankton.

Seasonal variations of zooplankton biomass largely depend on physical conditions since egg developement is temperature dependant (Moss, 1982).

Morgan (1980) concluded that temperature and sufficient food of suitable quality are the controlling factors for zooplankton production.

In the present study primary production was very low from January to April comprising only 2% of the annual production due to low incident light energy. The phytoplankton community during this period was dominated by diatoms. Comparatively higher efficiency of energy transformation during this period than the rest of the time could be due to both suitability of diatoms as food of zooplankton and optimum temperature for the growth and reproduction of zooplankton.

The highest zooplankton biomass was in May when phytoplankton was dominated by Dinobryon divergens which is a very good source of food for many species of zooplankton (Hutchinson, 1967; Schindler, 1972). Primary production levels remained high during the whole summer due to successful growth of several species of green and blue green algae but the efficiency of energy transfer was very low. Fifty seven percent of the annual production occurred from

June to August and the phytoplankton was dominated by Sphaerocystis schroeteri, Oocystis spp., and Cryptomonas spp. Moss (1982) reported that various species of algae are assimilated by zooplankton to differing extents. Some of them pass out of the gut of zooplankton alive, others dead but only partly digested. Sphaerocystis schroeteri, a thick cell walled algae embeded in a gelatinous sheath which decrease the digestibility of the algae and increase the possibility of gut passage (Porter, 1975). Porter (1976) observed that more than 90% of the unassimilated cells of S. schroeteri were alive after gut passage. Oocystis spp., have also been reported to be poorly assimilated (Moss, 1982). Blue green algae also have a reputation for being poorly assimilated food for many species of zooplankton. Arnold (1971) has shown that indefinite maintenance of Daphnia populations is not possible on certain blue green algal species.

In the present study, it seems likely that low energy transfer from phytoplankton to zooplankton could be due to poor assimilation of the green and blue green algal species.

After autumn overturn, primary production increased in October but the efficiency of energy transfer remained very low during the whole autumn. During this period, phytoplankton was dominated by green flagellates,

Cryptomonas spp., and Botryococcus braunii. Low rate of energy transformation during this period could again be related to poor assimilation of the algal species.

9.3. Primary production - Seston production :

On an annual basis less than 1% of the energy was transformed from phytoplankton to zooplankton (section 9.2), the rest may have joined the seston although some may have gone directly to other secondary producers like littoral benthos and fish which is beyond the scope of the present study. An amount of this unused energy fixed during primary production may go to the sediment through seston but some may be lost as heat or in respiration during the sedimentation and death and decomposition. During decomposition process, some organic matter may be dissolved into the water column and used again by phytoplankton in the form of nutrients. Fine particulate organic detritus may originate from both autochthonous and allochthonous sources and is extremely difficult to identify the amount originating directly from phytoplankton. In the present study, no attempt was made to separate organic matter of different origin and the seston will be treated as a whole.

Seston production varied greatly between upper (1m depth) and lower (9m depth) traps.

Although phytoplankton production was very low during March and April (0.34 x 10^5 to 0.55 x 10^5KJ/m^2/month), seston production in the upper trap remained high (2.3 x 10^5KJ/m2/month). With rapid increase of primary production in May (13.76 x 10^5KJ/m^2/month), seston biomass increased slightly (4.2 x 10^5KJ/m^2/month) and with primary production increasing in June and to the highest level in July (15.29 x 10^5KJ/m^2/month), seston production increased to 8.9 x 10^5/m^2/month. Although phytoplankton production declined sharply in August, seston reached to the highest peak of production (10.7 x 10^5KJ/m^2/month).

Primary production increased again in September (7.93 x 10^5KJ/m^2/month) but seston production declined sharply (2.83 x 10^5KJ/m^2/month) and again increased (3.46 X 10^5KJ/m^2/month) with increased primary production in October (12.32 x 10^5KJ/m^2/month). Primary production declined rapidly in November (2.9 x 10^5KJ/m^2/month) and reached to the lowest level in January, 1986, seston production declined more slowly but also reached to the lowest level in January (1.47 x 10^5KJ/m^2/month), although levels were higher than for primary production.

Seston production exceeded primary production more during March (>590.3%) and April (>448.4%) than at any other time in the period of study. It also exceeded in August (>149.7%) and from November (>13.37%) to January (>142.98%), 1986. However, during the period of high production in May, 30% of the energy channelled to the seston. It increased rapidly in June and reached to 58.66% in July. It declined sharply in September and reached to 28.05% in October. Thus for the period of overturn, seston exceeded phytoplankton production and for the period of stratification the reverse was the case except for August.

In the bottom trap, seston production during March (4.48 x 10^5KJ/m^2/month) and April (6.05 x 10^5KJ/m^2/month) was comparatively higher than the upper trap and was much higher than primary production. With increasing primary production in May and June, seston production declined to 2.6 x 10^5KJ/m^2/month. It increased slightly in July (3.78 x 10^5KJ/m^2/month) when the primary production was at the highest level. Seston production increased very rapidly to the highest level (9.37 x 10^5KJ/m^2/month) in August although primary production declined sharply. During the autumn peak of primary production in October, seston production declined sharply to the lowest level (2.46 x 10^5KJ/m^2/month). Seston production increased rapidly in November (5.82 x 10^5KJ/m^2/month) with rapid decline of primary production and

high level of seston (4.5 x 10^5KJ/m^2/month) remained from December to February, 1986 when primary production level was minimum.

Seston production also exceeded primary production during March (>12.09%) and April (>992.5%) at a greater rate in the bottom trap than in the upper trap. It exceeded primary production approximately 118% in August and 99% in November and reached to the highest level in December (>1538.77%) and the level also remained high in January (>445%), 1986. However, 33.57% of the energy was channelled to the seston in May, it declined slightly in June and then increased to 36.16% in September and again declined to 19% in October.

Increase in seston production in the upper trap from May to July and the highest level in August was due to the decomposition of phytoplankton which were caught immediately after their death. Comparatively lower levels of seston production in the bottom trap than the upper trap during June and July when primary production level was the highest, could be related with the sedimentation time of dead and decomposed phytoplankton and consequent loss of energy in the process. During this period thermal stratification could also play an important role in delaying the sedimentation of seston and preventing the resuspension of organic matter

from the sediment. As sedimenting seston reached the bottom trap by August, it was reflected by the highest level of seston biomass. The organic matter during this time seems to be originated mainly from phytoplankton. The other sources include inflow carrying allochthonous organic matter from the neighbouring area to the lake. Littoral vegetation and leaf litter from the catchment and resuspension of organic matter from the littoral and littori - profundal sediment could also contribute significantly. It is extremely difficult to quantify the contribution of these sources to the energetics of seston due to the complex nature. Direct relationship between phytoplankton production and seston biomass is common in many lakes (Wright, 1959; Wetzel, 1972; Jonasson et al.,1974; Hallegraeff, 1978). Although phytoplankton is the dominant source of organic detritus in many lakes, very few estimates of the rate of production of detritus from algae are available (Saunders, 1980).

High seston production during March and April which greatly exceeded primary production, could be related with the sedimentation of organic detritus originated mainly from the death and decomposition of aquatic macrophytes during the previous winter. The littoral area of Dubh Lochan have dense beds of both submerged and emergent vegetation. As autumn proceeds and temperature drops, these littoral macrophytes start dying and by winter most of these

vegetations die and subsequently decomposed in the lake water. Larger particles settle first and the smaller particles remain in suspension until reaching the deeper waters (Clay & Wilhm, 1979).

The inflow of rain water during March and April was very low and possibly therefore, the input of allochthonous organic matter was also low. High seston production during this period could, therefore, be resulted mainly from the death and decomposition of aquatic macrophytes since previous winter and the resuspension of organic matter from the sediment. On measuring the seston biomass by traps, Lastein (1983) reported the highest value of the year in April near the bottom.

At the time of autumn overturn (October), the circulation of water and the resuspension of organic matter from the sediment could be important in increasing seston biomass. However, during late autumn and winter, high quantities of seston could originate from both littoral vegetations and allochthonous sources as the inflow of rain water during this period was also high. During this period leaf litter could also contribute significantly into the composition of seston.

Saunders (1980) reviewed the role of macrophytes in the

production of organic detritus in lake ecosystems and suggested that they may produce detritus throughout the year. The major input of dead particulate matter occur with the changes of environmental condition in temperate region during autumn and is mainly related to the life cycle of the aquatic plants. It was also concluded that in the lake ecosystems, the nonliving organic matter is greater than the living matter by several orders of magnitude. Several workers reported the dominance of macrophytic organic matter in the seston in shallow oligotrophic lakes in temperate region (e. g. Bodin & Nauwerck, 1968; Hobbie et al., 1972; Wetzel & Hough, 1973). Wetzel et al.,(1972) reported an annual input of carbon in Lawrence lake in U.S.A., where macrophytes contributed more than twice as much as phytoplankton. However, the role of macrophytes and their composition in the seston is extremely variable depending upon the nature of the lake and the mode of life of individual species.

The contribution of allochthonous organic matter varies in different lakes and may also vary significantly in a particular lake in different seasons (Rodhe, 1969; Odum, 1971; Saunders, 1980). The informations on allochthonous organic matter are mostly qualitative because of difficulties in quantitatively estimating all the input rates associated with any single water body. Most

inventories of allochthonous input to water bodies are partial because selected sources have been estimated in the form of proximate indices of area or indices of fertility of the drainage basin. The proportion of allochthonous organic matter to the seston in lake varies from a few percent in the case of most surface drainages to more than 90% for litter fall (Leach, 1975; Saunders, 1980).

Ignoring the contribution of autochthonous macropytes and allochthonous sources in the seston, 72% and 77% of the primary production channelled through the upper and lower traps respectively and ultimately reached the sediment. High seston biomass also in the upper trap was contributed by sedimenting phytoplankton during the summer months when the productivity levels were high. During July and August seston biomass was also influenced by algal growth in the seston tubes of the upper trap.

9.4. Primary production - Sediment :

On an annual basis approximately 77% of the primary production of phytoplankton is channelled through seston and joined the sediment. The effect of the sedimented seston upon the energetics of sediment will be discussed in this section.

In deep water at station 1, the energy content of the sediment was high in July (0.0945 x 10^5KJ/g) when the primary production was at the highest level. Although primary production declined sharply in August, the energy content of the sediment reached to the highest level (0.10542 x 10^5KJ/g) with the highest level of sedimented seston. With increased primary production and rapid decline of seston biomass in September, the energy content of the sediment remained high. Sediment energetics declined slightly (0.0861 x 10^5KJ/g) with seston biomass although primary production increased to the autumn peak in October. Coinciding with the rapid decline of primary production from November, the energy content of the sediment declined gradually to the lowest level (0.0388 x 10^5KJ/g) in March, 1986 when seston biomass remained high. The energy content of the sediment again increased gradually from April (0.05502 x 10^5KJ/g) to June (0.0756 x 10^5KJ/g) with increasing primary production although seston biomass showed a declining tendency.

At station 2, the energy content of the sediment showed similar patterns of seasonal variations with primary production as was observed at station 1 but on an average the values were 25% lower than at station 1.

The energy content per unit of sediment at both the

stations showed close relation with the energy content per unit of seston at 9m depth but the sediment energy were always lower than seston energy.

In deep water at station 1, the energy content per gram of sediment was at the highest level from July to September (0.0945 x 10^5 to 0.10542 x 10^5KJ/g) when the energy content per gram of seston was also at the highest level (0.126 x 10^5 to 0.13986 x 10^5KJ/g). With rapid decline of seston energy in October (0.0945 x 10^5KJ/g), energy content of the sediment declined rapidly (0.086 x 10^5KJ/g). Sediment energy declined gradually from November (0.0735 x 10^5KJ/g) and reached to the lowest level in January (0.0512 x 10^5KJ/g), 1986 due to gradual decline of the energy content per gram of seston. The lowest level of energy in the seston during February (0.0735 x 10^5KJ/g) and March (0.08022 x 10^5KJ/g) was also reflected in the energy content of the sediment (0.0525 x 10^5 to 0.0546 x 10^5KJ/g). With increasing energy content of seston from April to June (0.09030 x 10^5 to 0.10^{5}KJ/g), the energy content of the sediment also increased and again reached to high level in June (0.0756 x 10^5KJ/g).

At station 2, the energy content per unit of sediment also showed close relationship with the energy content per unit of seston. It ranged from 0.07202 x 10^5KJ/g in August

to 0.0388 x 10^{-5}KJ/g in February, 1986. The energy content of sediment showed similar patterns of seasonal variations as was observed at station 1 but the levels were always lower particularly during the periods of hypolimnetic anoxia at station 1.

Comparatively higher levels of energy in the sediment at station 1 than station 2 during the whole period of study could be related to the differences in the supply of organic and mineral matter, decomposition process under aerobic and anaerobic conditions and the consumption of organic matter by the benthic organisms.

The absolute amount of organic matter in the deep water sediment at station 1 was always higher than in shallow water at station 2 (Fig. 65). The relative amount of organic matter with respect to mineral matter will also be higher in the deep water sediment because the sediment in shallow water receives more mineral particles from the edge of the lake.

The decay under anaerobic condition which occur from late July to September in the sediment at station 1, is slower than under aerobic condition which always occur at station 2 at least for the more mobile matter.

In shallow water at station 2, benthos biomass was comparatively higher than station 1 from March to September, therefore, the consumption of organic matter will be higher which would lead to a lowering of the energy content of the sediment in that period.

The sediment surface at station 1 was completely deoxygenated from mid July to late September where as at station 2, it remained well oxygenated, with saturation never dropping below 55%.

The rapid increase of primary production from late spring to mid summer was not reflected in the energy content of the sediment, instead the highest level of sediment energy was observed in August and September when primary production declined sharply. This relationship was probably due to the delay in the sedimentation process of phytoplankton from the upper layer to the bottom of lake. The highest level of energy content of the sediment during August and September could be due to the effect of thermal stratification, preventing mixing and resuspension of organic matter from the sediment. Comparatively lower levels of energy content of the sediment during early autumn than in the summer could be due to the effect of circulation and resuspension of organic matter and deposition of mineral particles in the sediment. Low energy content of the

sediment during the winter could also be related to continuous resuspension and deposition of mineral particles leading to a less organic sediment. During late autumn and winter primary production was very low but the energy content of the sediment did not decline at a similar rate because the sediment received organic matter from other autochthonous as well as allochthonous sources. During the present study neither the rate of sedimentation of phytoplankton nor the contribution of other sources of organic matter to the sediment was determined. It is, therefore, difficult to examine properly the relationship between primary production and the energy content of the sediment. However, the energy content of the sediment was high during high primary production in summer and declined during autumn and winter with declining primary production.

Although total seston biomass was comparatively lower during the summer months than the rest of the period except the highest level in August, energy content per unit of sediment remained high. Comparatively higher energy content of the sediment during summer than the rest of the period could be due to the increase in absolute amount of organic matter in the sediment (Fig. 65). The high energy content of the sediment during this period could be due to high contribution of phytoplankton in the seston as the energy content per unit of seston was much higher than the rest of

the period. Storr et al., (1984) reported that the energy content of the sediment in lake Erie reached to the highest level in July with maximum rate of plankton rainout. Although total seston biomass remained high from November to April, the energy content per unit of sediment declined to very low level. This decline was probably due to low energy content per unit of seston which originated mainly from the death and decomposition of aquatic macrophytes as well as allochthonous sources. Gorham & Sanger (1967) examined the energy content of the sediment of different types of lakes as well as the source materials. They concluded that the source material dominated by phytoplankton had much higher energy content than the aquatic macrophytes.

9.5. Primary production - Benthos biomass :

It was seen in the previous sections that 77% of the energy from primary production channelled through seston to the sediment. The seasonal variations of sediment energy were generally influenced by the energy content of seston. The effect of seasonal variations of sediment energy upon the benthos energetics will be discussed in this section.

The calculations of the efficiency of energy transfer from phytoplankton to benthos is not correct in strict sense because benthic organisms feed mainly on detritus but not on

living phytoplankton. Detritus originate from both autochthonous and allochthonous sources and is extremely difficult to quantify the contribution of each source. In addition, the problem in the present study is that the data on benthos biomass is used to calculate the efficiency of energy transformation from phytoplankton and seston production which is again not correct in strict sense. However, an attempt is made in the present study to calculate the efficiency of energy transformation from phytoplankton to benthos to assess the seasonal patterns of energy flow.

The seasonal variations of benthos biomass greatly differed between the two stations (Table 9).

In deep water at station 1, benthos biomass was high during March (0.269 x 10^5KJ/m2/month) and April (0.393 x 10^5KJ/m^2/month) when primary production was very low. During this period seston biomass was fairly high but the energy content per gram of both seston and sediment were low. With rapid increase of primary production in May, benthos biomass reached to its first peak (0.442 x 10^5KJ/m^2/month) when seston biomass was still high and the energy content per gram of both seston and sediment increased slightly. Benthos biomass declined slightly in June (0.368 x 10^5KJ/m^2/month) with increasing primary production. During this period

seston biomass declined sharply but the energy content per gram of both seston and sediment increased rapidly. Primary production reached to the highest level in July but benthos biomass declined sharply (0.221 x 10^5KJ/m^2/month) although the energy content of both seston and sediment remained high. Benthos biomass declined to very low level in August with rapid decline of primary production but seston biomass and the energy content per gram of both seston and sediment reached to the highest level. With increasing primary production and high energy content of seston and sediment, benthos biomass remained low (0.172 x 10^5KJ/m^2/month) in September. It increased sharply in October when primary production increased to the second maximum but seston biomass and the energy content of both seston and sediment was declining. Seston biomass increased to the second peak in November (0.427 x 10^5KJ/m^2/month) and high level remained in December with high seston biomass although primary production and the energy content of both seston and sediment declined to very low level. Rapid decline of seston biomass in January, 1986 (0.221 x 10^5KJ/m^2/month) and the lowest level in February (0.135 x 10^5KJ/m^2/month) was accompanied by the lowest level of primary production and the energy content of the sediment although total seston biomass remained high.

At station 2, benthos biomass showed close relationship

with primary production and the seasonal pattern was quite different from station 1. Low level of seston biomass in March (0.172 x 10^5KJ/m^2/month) and April (0.184 x 10^5KJ/m^2/month) was probably due to low primary production. Rapid increase of benthos biomass in May (0.454 x 10^5KJ/m^2/month) and high level up to August (0.331 x 10^5KJ/m^2/month) coincides with the seasonal patterns of primary production. It declined sharply in September and reached to very low level in November (0.074 x 10^5KJ/m^2/month) and again increased slightly in December and January (0.093 x 10^5KJ/m^2/month) after the autumn peak of primary production. With very low level of primary production from December to February, 1986, benthos biomass declined rapidly and reached to the lowest level (0.061 x 10^5KJ/m^2/month) in February, 1986.

The efficiency of energy transformation from phytoplankton to benthos showed great seasonal variations. The efficiency also varied greatly between the two stations (Table 9).

At station 1, the efficiency of energy transformation from phytoplankton to benthos ranged from 1.44 to 550%. The efficiency was high (78.83%) in February and then declined slightly in March (70.91%). It declined very rapidly in May (3.21%) and then a gradual decline lead to the lowest level

in July when the lake was thermally stratified and the sediment surface was completely deoxygenated (Fig. 5). The efficiency increased slightly (3.48%) in August and then decreased gradually to 2.09% in October. It increased very rapidly from November (14.3%) and reached to the highest level (550.27%) in January, 1986.

At station 2, the efficiency of energy transformation from phytoplankton to benthos ranged from 1.19 to 2.32%. The efficiency was also high (50.16%) in March and then declined slightly in April (33.24%). It declined rapidly to 3.29% in May and then declined gradually to 2.49% in July. The efficiency again increased to 7.73% in August and then declined gradually to the lowest level (1.19%) in October. It increased slightly in November (2.52%) and then a rapid increase through December lead to the highest level (232.33%) in January, 1986.

On an annual basis, 74.22% and 33.75% of the energy were transformed from phytoplankton to benthos at station 1 and station 2 respectively.

Many workers used a ratio of benthos biomass to primary production to evaluate the efficiency of energy transformation in natural communities (e.g. Iwakuma et al., 1984; Kajak & Rybak, 1966; Jonasson, 1979). Blazka et

al.,(1980) discussed the efficiency of secondary production and concluded that the seperate listing of efficiencies of zooplankton and benthos respectively is not strictly correct as these two components are not independent of one another and some other parameters determine the partitioning of primary production between them. However, Jonasson (1979) compared the efficiencies of energy transformation from phytoplankton to benthos of 11 temperate northern lakes and the ratios calculated ranged from 0.77 to 6.3%. Brylinski (1980) reviewed the literature on the efficiency of energy transformation from phytoplankton to benthos and reported values between 0.16 and 11.1%.

In the present study, the efficiency of energy transformation from phytoplankton to benthos varied between 1.19 & 7.73% during most of the time except two unusually high values during March and April and in December and January, 1986 when they exceeded primary production resulting very high efficiency on an annual basis. These unusually high values were due to very low primary production in comparison with benthos biomass.

Morgan (1980) reviewed the literature on benthos biomass and concluded that in the profundal zone of stratified temperate lakes, maxima occur mainly in spring (April, May) and autumn (October) and in littoral areas a

single summer maximum in July is common.

High efficiency of energy transformation during early spring in both the stations and the highest level during late autumn at station 1 could be related to a combination of optimum environmental conditions especially temperature and the supply of high energy content algal food. With rapid increase of primary production from May, the energy content of the sediment increased gradually and reached to the highest level in August but the efficiency of energy transformation declined gradually to very low level in July, September and October at station 1 which could be due to the effect of deoxygenation of the sediment. Jorgensen (1980) clearly demonstrated that oxygen supply was a limiting factor for several species of benthos in lake Limfjorden (Denmark). In the present study, Chironomus plumosus was the only species recorded at station 1 which has rather high ability to survive longer time in deoxygenated condition due to its haemoglobin content. Moss (1982) reported that the respiration rate of C. plumosus decline with rapid decline of dissolved oxygen in the hypolimnion and the growth of C. plumosus larvae stops when the sediment is deoxygenated.

Iwakuma et al., (1984) reported that the seasonal variations of Chironomid biomass was independent of the fluctuations of primary production in lake Kasumigaura

(Japan). The environmental factors such as temperature and dissolved oxygen were the controlling factors in the production of C. plumosus which is also true in the deep water at station 1 in Dubh Lochan. To the contrary, Jonasson (1972) demonstrated a clear dependance of Chironomid secondary production on the primary production in lake Esrom. In the present study, the sediment surface at station 2 was always well oxygenated and comparatively higher efficiency from May to August when the energy content of the sediment was high, seems to be related with the supply of high energy content algal food. The rapid decline of the efficiency of energy transformation to the benthos during late spring to early summer could also be related with the emergence of Chironomus plumosus as they become adult, leave the sediment and become terrestrial (Moss, 1982). As C. plumosus was the only species of benthos observed at station 1 and Chironomids were also dominant at station 2, the export of energy to the terrestrial ecosystem could also be a very important factor. Most of the studies on Chironomid emergence are qualitative, used mainly in taxonomic studies and the quantitative information is rare. It is extremely difficult to obtain such informations quantitatively in natural environment as their growth and maturity may take from few months to few years (Sadler, 1935; Konstantinov, 1958; Tubb & Dorris, 1965) depending on the suitable environmental condition and appropriate quality and quantity

of food supply (Morgan, 1980). However, in the present study, no attempt was made to quantify such energy export from the sediment.

CHAPTER — 10.

CONCLUSIONS

The environmental conditions in the Dubh Lochan have changed a great deal over the last 10 years since Klarer's (1978) study. The pH declined markedly which may be due to acid rain. Nitrate and silicate concentrations increased but concentrations of orthophosphate declined. Nutrient concentrations were controlled both by biological activity (primarily in the upper waters) and by oxygen depletion (primarily in the lower waters) during thermal stratification.

Phytoplankton biomass showed single summer peak in both the years during June and July. Green and blue green algae dominated during most of the time except in late autumn and winter when diatoms dominated the sparse phytoplankton community.

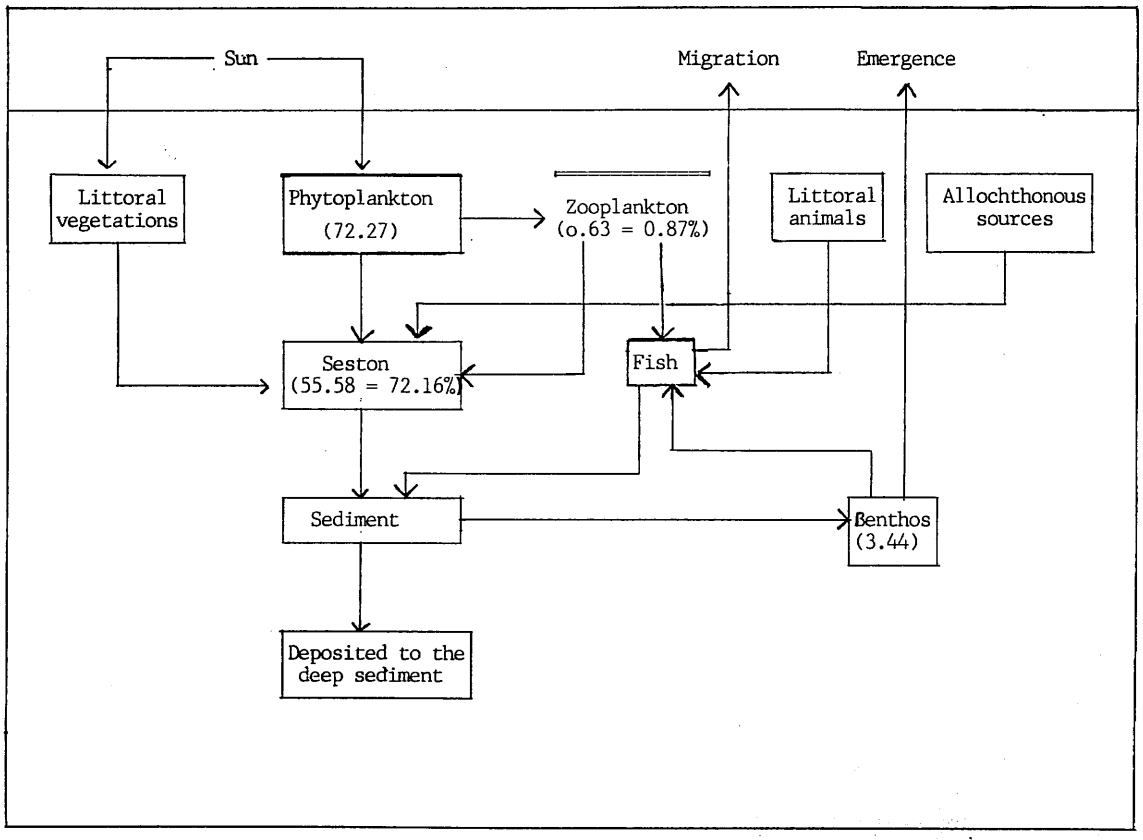
Zooplankton biomass showed three distinct seasonal peaks during mid to late spring, late summer to early autumn and in late autumn to early winter. Although phytoplankton biomass was the highest in June and July, zooplankton biomass did not increase at a similar rate. During this period Sphaerocystis schroeteri was the dominant species

among phytoplankton which was not a suitable food for zooplankton. During late spring and late autumn high zooplankton biomass was due to optimum environmental conditions and the increased production of diatoms which is a very good source of food.

Seston traps placed 1m below the surface was not suitable for seston collection because of periphytic algal growth inside the tubes during the summer months. However, seston biomass showed three distinct seasonal peaks in mid spring, late summer and mid autumn although high levels were also observed in winter. The late summer peak seems to be related to maximum phytoplankton production during mid summer and the two other peaks could be due to non-algal autochthonous detritus as well as allochthonous organic matter.

Nitrogen, orthophosphate and carbon content of the sediment were always higher in the flocculent layer than the rest of the sediment. The levels were always higher at station 1 than station 2. They were greatly influenced by the sedimenting seston. The release of nutrients from the sediment especially ammonia and orthophosphate were reflected by rapid increase of the nutrients in the water above the sediment during the periods of hypolimnetic anoxia. During this period the energy content of the

Figure 69. Energy flow in Dubh Lochan. The values are expressed in KJ x 10^5/year.



sediment at station 1 increased to the highest level due to anaerobic decomposition of organic matter in the sediment. High energy content of the sediment during the summer months in both the stations seems to be due to the high contribution of algal detritus sedimenting through seston to the sediment.

Benthos biomass in deep water at station 1 was independant of primary production but in shallow water at station 2, it closely followed primary production. Environmental factors especially temperature and dissolved oxygen rather than the supply of food seem to be the limiting factor for the benthic organisms in deep water at station 1.

A possible energy flow pattern in Dubh Lochan is shown in Figure 69. The energetic values are presented only for those parameters which were determined in the present study.

On an annual basis 0.87% of the energy was transformed from phytoplankton to zooplankton ranging from 0.08% in October to 5.89% in February. High efficiency from January to April could be due to both suitability of diatoms as food for zooplankton and optimum environmental conditions for their growth and reproduction. Low efficiency during the

summer months could be due to poor assimilation of the green and blue green algal species by zooplankton.

Ignoring the contribution of allochthonous organic matter, 77% of the energy from phytoplankton was channelled through seston to the sediment and was greatly influenced by the environmental conditions especially temperature and the depletion of oxygen in the hypoloimnion during the summer months.

The efficiency of energy transformation from phytoplankton to benthos varied between 1.19% and 7.73% during most of the time except two unusually high values during March & April and in December & January, 1986 when they exceeded primary production.

In the light of my experience during the present study, future work on energy flow in Dubh Lochan should include an examination of periphytic and benthic algae especially diatoms, littoral benthos and the contribution of non-algal autochthonous as well as allochthonous organic matter in to the energetics of seston and sediment.

CHAPTER — 11.

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